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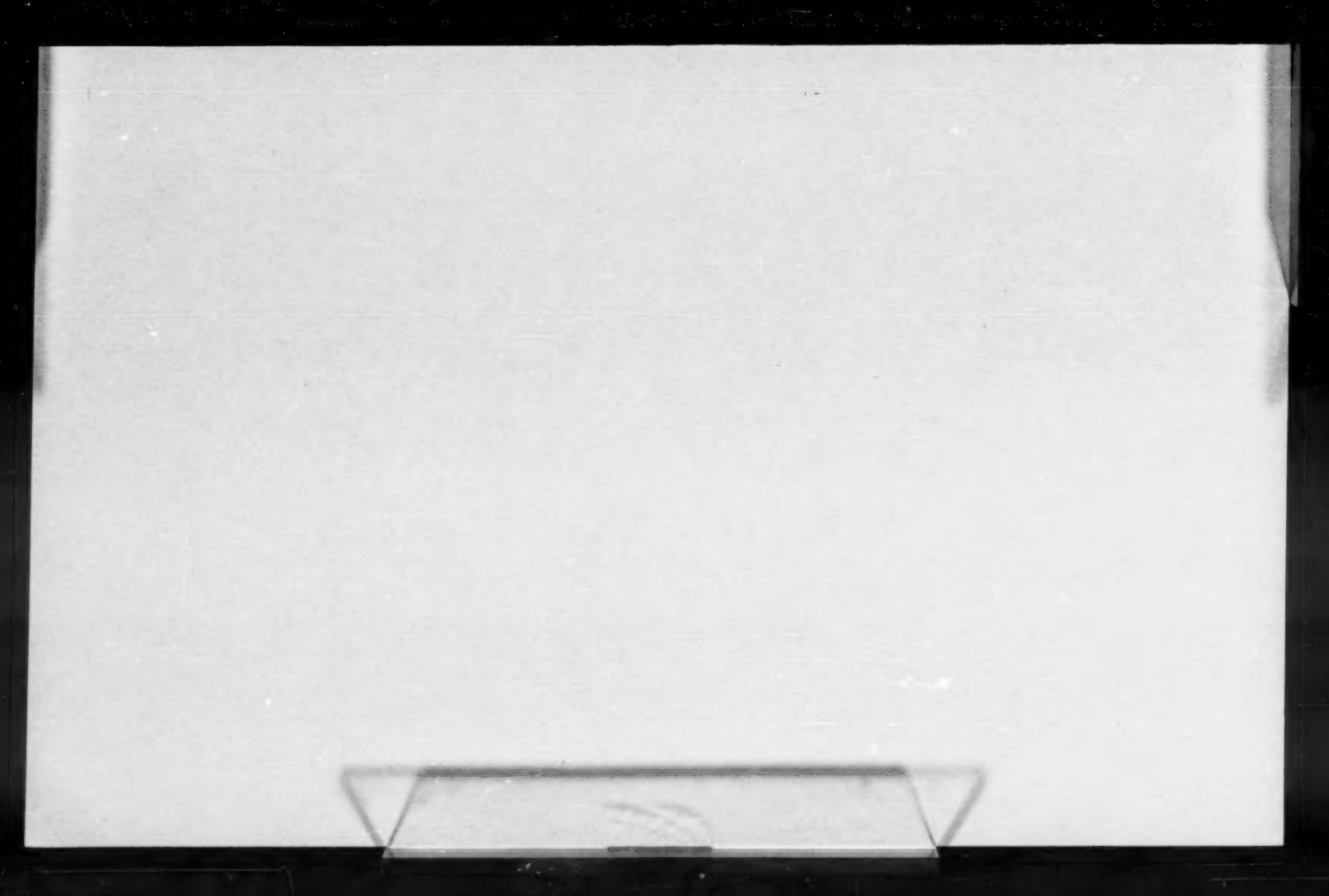

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METASOMATIC GRANITIZATION OF BATHOLITHIC DIMENSIONS

PART III. RELATIONSHIPS OF SYNKINEMATIC AND STATIC GRANITIZATION

PETER MISCH

ABSTRACT. Part III consists of a discussion of the relations between synkinematic granitization as described in Part I, and static granitization as treated in Part II. Three areas in which both occur are briefly described. In the synkinematic gneisses of Nanga Parbat, relatively small aplitic-pegmatitic bodies formed after orogeny had ceased. In the adjacent noritic masses, static granitization produced small quartz-dioritic and granodioritic bodies. At Ts'angshan in West Yunnan, Archaean gneisses show synkinematic granitization, but on a local scale granitization continued after the end of deformation. Continuous structural evolution from synkinematic to static forms of granitization is described. West of Riverside in North Central Washington, Paleozoic rocks have been intensely deformed, variously metamorphosed, and partially granitized. There are all transitions from synkinematic to static granitization. The latter has formed large "eugranitic" masses and in a number of places extended beyond the limits of synkinematic granitization.

Criteria for synkinematic and static granitization are summarized. Genetically, synkinematic granitization is presented as a fundamental process in geosynclinal orogeny, and static granitization as its continuation after the end of orogeny. Postorogenic conditions favor a carrying of the process into higher levels of the crust. Where only static granitization is visible, the products of previous synkinematic granitization may be concealed at depth. Granitic batholiths are considered as predominantly metasomatic, and the rise of magma in broad fronts to shallow levels without breaking through as unlikely. Mobilization of metasomatized rock masses may more locally occur as a still more advanced stage of granitization. To sum up, genetic unity of synkinematic and static granitization in geosynclinal belts is emphasized.

INTRODUCTION

IN Part I synkinematic granitization of batholithic dimensions has been described, and in Part II static granitization on a similar scale has been treated. Emphasis has been on the evidence for regional metasomatism, as against igneous intrusion. The subject of Part III is the genetic relationship of synkinematic and static granitization. Prior to the general treatment of this subject, some examples are given from areas

in which synkinematic and static granitization occur together. Emphasis is mainly on the distinction between and the relationships of the synkinematic and the static process. In order to avoid repetition, the evidence for metasomatism as such is only briefly sketched in these areal descriptions, particularly where such evidence is similar to that offered in Parts I and II, and additional data apply only to modifications not treated in Parts I and II. The areas have been selected so as to offer some variety, with regard to time relations, chemical environment, and relative scale of synkinematic and static granitization.

I. NANGA PARBAT AREA, NORTHWEST HIMALAYAS

The first example is the Nanga Parbat region which was described in Part I as a typical case of synkinematic replacement on a vast scale. Later, statically formed granitic rocks are subordinate in this region, and are not as grandly displayed as in some other areas, but this region has been selected as an example because the general background of synkinematic transformation has been established in Part I.

I do not refer to those synkinematic granitic gneisses in wide parts, and especially the interior, of the Nanga Parbat massif, in which crystallization lasted somewhat longer than deformation (cf. Part I). This does not establish a separate phase of static replacement, but merely indicates that temperature was still high in these rocks when orogenic deformation ceased. Not even cross-cutting pegmatites or aplites were formed at this stage, but all mechanical lattice disturbances were obliterated. The statically formed rocks with which we are concerned are distinct bodies of later granitic rocks which lack schistosity and transect the structures of the rocks described in Part I. These bodies comprise two varieties which are associated with country rocks of different chemical composition. They are (a) mostly tourmaline-bearing acidic granites in the gneiss massif, and (b) quartz-diorites and granodiorites in the masses of altered Eocene norites.

(a) *Tourmaline-granites in Nanga Parbat gneiss massif*

The tourmaline-granites occur in discordant bodies, comprising small dikes and large dike-like and lenticular masses which attain a maximum size of a few miles and are thus still

very small compared to the huge area of synkinematic granitization in which they are irregularly scattered. The *field relations* of most of the larger masses suggest a replacement origin rather than forceful mechanical intrusion (cf. fig. 1, and pl. 1, fig. 1). Generally no signs of mechanical displace-

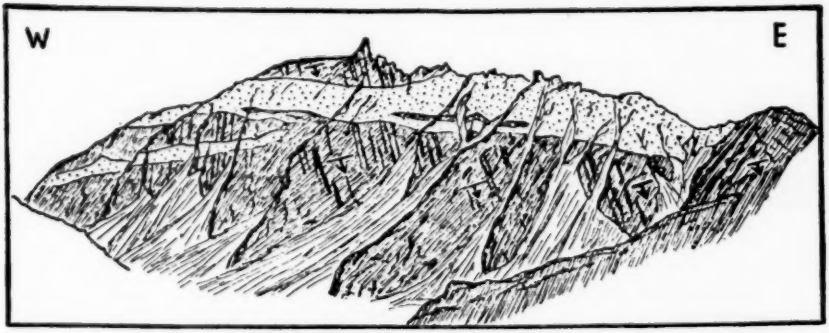

Figure 1. Postorogenic tourmaline-granite in synorogenic granitic biotite-flasergneiss. South face of Jabardar Peak (14,800′), 12½ miles north of Nanga Parbat. The face is about 4,000 feet high. After Misch (1935, fig. 23).

ment of the structures of the enclosing gneisses were observed. At several localities thin septa and lenses of gneiss are preserved within the granite without having been disturbed or disrupted. At least some of the small dikes show field features suggestive of replacement (cf. G. E. Goodspeed's 1940 criteria for replacement and dilation dikes). An example is shown in plate 1, figure 2, in which fracture control is also indicated. There is, however, a possibility that some of the dikes and dike-like masses were formed by dilation and actual injection of mobilized material. Further detailed field work would be required to clarify this point.

The rocks are all very leucocratic. Many have an aplitic, some a pegmatitic character. The main constituents are *quartz*, *potash-feldspar*, and *sodic plagioclase* (partly albite, partly albite plus oligoclase, and rarely oligoclase alone; mostly zoned). In nearly all specimens the quartz-feldspar fabric is *crystalloblastic*. Quartz and feldspar interlock and penetrate each other. Myrmekite is common. Occasionally large porphyroblasts of potash-feldspar enclose the other minerals. More or less recrystallized cataclastic structures sometimes occur. They indicate a continuation, during the crystallization

of the rock, of tectonic fracturing which was presumably an important factor in determining the original location of the scattered granitic bodies.

Only one specimen has an igneous-appearing texture, with subhedral feldspars and interstitial quartz, and two or three others combine igneous-appearing and crystalloblastic features. However, "interstitial" textures *can* form by replacement, as was seen in some granitized basic rocks in this area (cf. Ib), though in this particular tourmaline-granite local "rheomorphism," to use H. G. Backlund's term (1937; cf. also G. E. Goodspeed, 1948, 1949), is perhaps a more likely explanation. Action of hot gases may have helped to achieve this result. Their presence is indicated by "pneumatolytic" minerals.

Tourmaline is present in most specimens and varies, often in the same thin section, from irregular replacement shapes to perfect crystals some of which still contain quartz inclusions. Very locally tourmaline replaces biotite. Half of the tourmaline-bearing granites contain *fluorite* which irregularly replaces feldspar. One specimen contains *topaz*. In some of the granites minor amounts of *biotite* occur as ragged grains which give the impression of being absorbed and replaced by felsic minerals. It is often marginally surrounded by later *muscovite* which may also replace feldspar. The biotite in the granites optically resembles that in the enclosing flasergneisses, and I would interpret it as a relic which has survived from the gneissic country rock. At contacts of granite and gneiss a similar absorption of biotite and formation of new muscovite can be observed. To a certain extent the disappearance of biotite is linked with the appearance of tourmaline.

The main mineralogical differences between the granites described and the granitic biotite-flasergneiss in which most of them occur, are the important role "pneumatolytic" minerals play in most of the granites, their very low content or complete lack of biotite, and the usually more sodic character of their plagioclase. A small amount of calcium is bound in the fluorite which in part of the granites replaces some feldspar, but as a whole the granites are poorer in calcium than the enclosing gneisses. The same holds true of iron and magnesium. It thus appears that the mineralogical-chemical differences between the original argillite-derived schists and the granitic

biotite-flasergneisses on the one hand, and between these latter and the acidic granites on the other hand, point in the same direction. A special feature in the scattered small granite bodies is concentration of boron and fluorine. An active role of hot gases is obvious, definitely at a late stage, and possibly even during earlier stages of the formation of these rocks.

Exceptionally, local static granitization of lime-silicate-granulites was observed in the interior of the Nanga Parbat massif. One example shows the typical lime-silicate mineral assemblage with an additional large amount of orthoclase the potash of which cannot have been derived entirely from the original argillaceous limestone. A more advanced stage of the same process seems to be represented by a small body of pyroxene-granite which consists of a large quantity of orthoclase and smaller amounts of plagioclase (An 31+), quartz, diopsidic pyroxene, and sphene. During a number of traverses of the gneiss massif only one single small outcrop of a granitic rock free from potash feldspar was met (a leucocratic biotite-quartz-diorite).

(b) *Quartz-dioritic and granodioritic rocks in the metanorite masses*

In contrast to the granites in the gneiss massif, *statically formed quartz-dioritic, trondhjemitic and granodioritic rocks* occur in the large metanorite masses bordering both sides of the gneiss massif (cf. fig. 1, in Part I). At the time of the metamorphic recrystallization of the basic masses, deformation was restricted to their margins, and to local zones in their interior, mostly near included metasediments. Otherwise, the metanorites are non-schistose. They include some finer-grained hornfelsic amphibolites part of which may be of sedimentary derivation. The synkinematic granitization in the Nanga Parbat massif has to some extent also affected the norite-derived amphibolites in the border zone where they are interfolded with the gneisses. Within the metanorite masses, static granitization has been active at many places though most of the individual transformed bodies are very small. This phase of static granitization appears to be later than the formation of the schistose amphibolites and of the synkinematic gneisses, for where it has affected schistose varieties of the basic rocks, it is later than the schistosity. On the other hand, it is prob-

ably somewhat earlier than the formation of the tourmaline-granites in the gneiss massif.

The small statically granitized bodies in the metanorite masses belong to the "eugranitic-appearing type" mentioned at the end of Part II. They form light-colored pockets and patches which spread out irregularly in the basic rocks and locally pass into replacement breccias where fracturing has occurred (pl. 2, fig. 1). There are also replacement veins and dikes. Elongated schlieren-like patches may occur where the country rock is weakly schistose (pl. 1, fig. 3). Contacts are locally sharp, especially where fracture control is visible, but are mostly gradational, and intermediate rock types are common. In the locally occurring schistose varieties of the basic rocks, weak relict schistosity has sometimes survived in granitized portions. That granitization was postkinematic, is shown in such cases by irregularly crosscutting contacts, and by a transverse orientation of some of the feldspar porphyroblasts (cf. below, discussion on crosscutting dikes with relict schistosity at Ts'angshan).

The granitized rocks are enriched in plagioclase and quartz, impoverished in mafics, much hornblende has been replaced by biotite, and some potash feldspar has formed. Muscovite occurs locally. The plagioclase has become more sodic than in the basic rocks (except where their plagioclase had, during recrystallization prior to granitization, already been completely broken up into epidote and oligoclase). The hornblende of the metanorites and hornfelsic amphibolites survives in some of the granitized rocks, whereas in others part or all of it is biotitized and potash-feldspar may also have formed. At contacts, biotitization may occur in the basic rocks.

All the granitized rocks are crystalloblastic. Sutured granoblastic textures are very common. Poikiloblastic growth, similar to that in the hornblende of many metanorites, is often seen in the granitized rocks. Plagioclase often forms replacement porphyroblasts enclosing small relict grains. Where potash-feldspar has formed in larger quantities, it mostly consists of similar replacement porphyroblasts. At several places, a peculiar recrystallization texture was noticed in relatively fine-grained intermediate rocks. Their plagioclase forms a xenoblastic polygonal pavement which may persist when the rock is enriched in plagioclase, but with further progress of

granitization gives way to more coarse-grained sutured-granoblastic textures.

Quartz occurring between crystalloblastic feldspars sometimes has the appearance of an "interstitial filling." Recrystallized mafics occasionally occupy a similar "interstitial" position. Generally textures are uneven. Hornblende and biotite, partly associated with epidote, are commonly concentrated in clusters which are recrystallized relics of the basic country rock and often grade into the latter. There are all passages from feldspathized rocks which still contain much of the fabric of the basic rocks between plagioclase porphyroblasts, to leucocratic rocks in which only minor amounts of unevenly scattered mafics have survived. Where relict schistosity occurs, it is usually marked by the mafics.

Some of the small granitized bodies bear evidence of local metamorphic differentiation, but in most cases an addition of alkali and silica from a more distant source is indicated by the composition of the original and the metasomatized rocks. Sodium is commonly the main alkali added, though part of the total sodium present was contained in the original rocks. Potash-feldspar is often absent, and only locally has it formed in larger quantities. Potash metasomatism is frequently confined to biotitization, and even this may be lacking. Where metasomatic potash-feldspar is present, it has mostly formed at a late stage of transformation.

The *chemical contrast between the granitic rocks in the gneiss massif, and the predominantly quartz-dioritic to granodioritic patches and veins in the metanorite masses*, is striking. It reflects the different chemical composition of the original rocks in both areas. This regional relationship is a strong additional argument in favor of granitization. The different sodium-potash ratio is in part directly due to the different composition of the country rocks, and in part to a selective character of metasomatism, basic rocks being primarily in need of sodium (and silica), and usually being able to absorb larger quantities of potash only at a later stage of their transformation (cf. Part I, pp. 237-238). Moreover, where metamorphic differentiation within the metanorites has contributed the main alkali transferred was, of course, sodium.

Larger bodies of "eugranitic" rocks which extend over several miles, were observed near the eastern border of the area,

both in the metanorites and the Cretaceous-Eocene volcanic formation. Their composition shows the same variation as that of the small granitized patches and veins, but as a whole rocks which, in addition to plagioclase, contain considerable amounts of potash-feldspar, are more common. Limited time did not permit collecting sufficient data on these rocks to warrant a general genetic interpretation. However, such data as were obtained, show that at some places metasomatic processes were active in the formation of these rocks.

The specimens obtained have coarse-grained granoblastic fabrics. Hornblende and biotite are unevenly scattered and often concentrated in clusters which suggest recrystallized relics of the basic country rocks. Poikiloblastic growth occurs. A granodiorite which covers a large area encloses, in a granoblastic plagioclase-quartz-hornblende fabric, large microperthite idioblasts which replace the granoblastic matrix and enclose numerous relics of hornblende, plagioclase and quartz. The porphyroblasts reach an inch across and are usually Carlsbad twins. Introduction of potash was the latest stage in the development of this rock. The granodiorite encloses more fine-grained relics of incompletely feldspathized hornfelsic amphibolites. As their transformation progresses, only clusters of more coarsely recrystallized hornblende remain.

East of Kalapani (cf. fig. 1 in Part I) a "eugranitic" rock mass is in contact with Eocene-Cretaceous basic lava. Near the contact, the basic rock has been statically recrystallized to a fine-grained compact hornfelsic amphibolite. Where fracturing had occurred in the basic rock, replacement breccias have formed at the contact. Within the breccia, contacts are partly sharp where formed by fractures, but there are also all gradations from the basic into the acidic rock. Plagioclase porphyroblasts developed in the basic rock, and the hornblende was more coarsely recrystallized. As feldspathization advanced, the hornblende became restricted to poikiloblastic relict patches and clusters. Quartz was introduced, and the rock became strongly leucocratic. At a comparatively early stage of transformation, tiny patches in the rock occasionally developed certain igneous-appearing microscopic features; plagioclase porphyroblasts developed crystal form, quartz grew between them, and thus an interstitial-appearing texture was produced. If such texture is found in a more fully granitized rock, as

for instance some miles farther north, it might be taken as evidence of an igneous origin, but obviously it can also form by metamorphic-metasomatic processes.

II. TS'ANGSHAN AREA, WEST YUNNAN (CHINA)[1]

(a) *Summary of synkinematic granitization in the Ts'angshan gneisses*

North of the Burma Road and west of the ancient town of Tali, the Ts'angshan range extends in a north-northwesterly direction, rising to over 14,000 feet. This region is near the eastern border of the geosyncline which I found to occupy West Yunnan, and is characterized by overthrusting to the east (Misch, 1945a and 1945b). One of the thrust masses consists of Archaean gneisses. It composes most of the Ts'angshan range. Near the thrusts bordering it below and above, this mass has suffered retrogressive dynamic metamorphism which was contemporaneous with progressive dynamic metamorphism[2] in Paleozoic and Mesozoic rocks. In the interior of the mass, the gneisses have remained unaffected. It is these rocks with which we are concerned. They originated from a thick succession of partly sandy argillites with subordinate basic layers. These rocks have been intensely folded and during this orogeny have been metamorphosed into fine-grained biotite-paragneisses and biotite-schists, quartzitic biotite-schists, and some more hornfelsic schists, with subordinate amphibolites (partly para-amphibolites grading into biotite-schists). Still during orogeny, these metamorphics have been variously granitized.

The metamorphic migmatites thus formed show, in field sections, hand specimens, and thin sections, a very close resemblance to the various gneisses of Nanga Parbat described in Part I which are representative of synkinematically granitized argillites the world over. The Ts'angshan gneisses com-

[1] My field work in the Ts'angshan area was done during a number of trips from 1939 to 1944 under the auspices of National Sun Yat-sen University, National University of Peking, Geological Survey of Yunnan, and a Committee for scientific exploration of the Tali area formed by Tali citizens and headed by General Tsung-Liu Ma. A report for publication in Chinese was submitted. I hope soon to publish the map and English report.

[2] I use the term "dynamic metamorphism" to indicate such low grade (essentially epizonal) metamorphism which can be demonstrated to have been caused by intense mechanical rock deformation (differential shearing, etc.) without any appreciable contribution by other factors (introduction of heat, metasomatism, etc.).

prise the same types of feldspar-porphyroblast-schists, augengneisses and banded gneisses which occur at Nanga Parbat. There are the same gradations between and the same interlayering of these types, the same variations in the proportion of non-replaced and of metasomatized material, and in the thickness of individual bands. The banded gneisses show the same evidence of having been formed chiefly by *lit-par-lit* replacement rather than true injection. There are also similar granitic biotite-flasergneisses. They have here developed from augengneisses. There are also zones of white microcline-gneisses which resemble certain rocks of Nanga Parbat. The schists and gneisses of Ts'angshan are essentially mesozonal.

The close petrographic similarity of the Ts'angshan and Nanga Parbat rocks and the presence of the same replacement features prove an identical origin. I may therefore refer to the genetic discussion in Part I. The main difference is that at Nanga Parbat the zones of progressive metamorphism and granitization are displayed in unusual completeness and regularity, whereas in the much older[3] rocks of Ts'angshan only part of the picture has been preserved, owing to post-Archaean erosion and to later folding and thrust-faulting.

(b) *Local postkinematic granitization*

Granitization in the Ts'angshan gneisses was chiefly synkinematic as is shown by sharp parallelism of bands, alignment and elongation of porphyroblasts, well-marked schistosity, and other megascopic and microscopic structural features. However, subsequent static replacement was widespread, although it occurred on a small scale and did not lead to the formation of any larger bodies of postkinematic granitic rocks within the gneiss mass.

Well-exposed examples are easily accessible near the Burma Road in a canyon which cuts across the southernmost part of the Ts'angshan range. Figure 2 shows a small pegmatite dike from this locality. On the one hand, it transects the schistosity of the country rock and is therefore later than the differential rock deformation, i.e. postkinematic. On the other hand, marked chiefly by coarsely crystallized biotite, it still possesses the schistosity of the country rock, and cannot therefore have

[3] Referring to the age of metamorphism and granitization, not of the original sediments, in both areas.

formed by postkinematic igneous intrusion cutting across the schistosity of the country rock. The obvious explanation is that the dike is of replacement origin. It is crosscutting because it is postkinematic, and it has inherited the schistosity of the country rock as a relict structure because it is metasomatic.

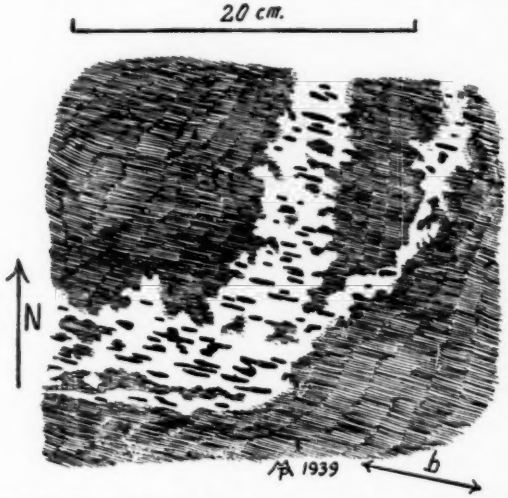

Figure 2. Postkinematic replacement pegmatite in fine-grained schistose biotite-gneiss. Erho Canyon, Ts'angshan, West Yunnan. Relics of schist in the pegmatite are shown in gray, coarsely recrystallized biotite in black. b = lineation.

This is confirmed by the crenulated border of the dike, by the presence of large feldspar porphyroblasts invading the country rock along the contacts, and by the preservation of undisturbed (neither shifted nor rotated) relics of the fine-grained schistose country rock within the dike ("skialiths," to use G. E. Goodspeed's 1948 term). Small pegmatite bodies of similar origin often occur in the Ts'angshan gneiss. Some of them have lost their relict schistosity, and may in some instances have actually moved.

Another example of static granitization is shown in figure 3. In this example also the metasomatized rock possesses relict schistosity, and has postkinematic contacts which irregularly transect the schistosity of the country rock. Contacts are partly gradational and partly sharp. It has been emphasized in an earlier chapter that granitization is capable of

forming sharp contacts, especially if there is joint or fracture control. Figure 3 shows, in addition to pegmatite, a more fine-grained, light-colored, somewhat aplitic granite with relict schistosity. Small bodies of this type of replacement rock are quite common in this area. Some of them have lost their relict

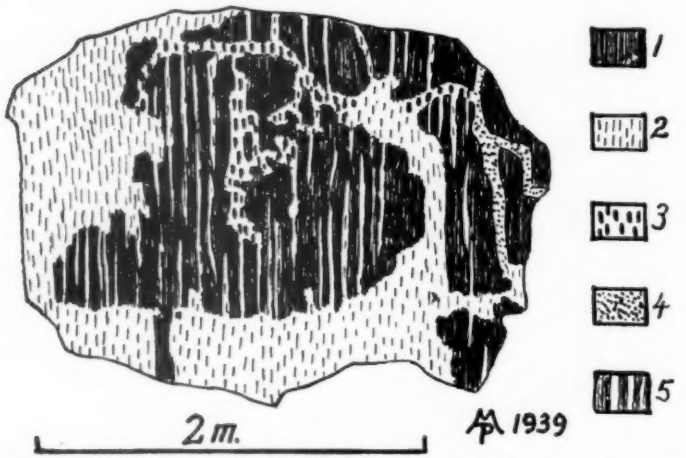

Figure 3. Postkinematic replacement in gneiss. Erho Canyon, Ts'angshan, West Yunnan.

1 = fine-grained schistose biotite-gneiss
2 = leucocratic granite } postkinematic replacement rocks, with gneissic
3 = pegmatite } relict schistosity
4 = quartz veins
5 = banded gneiss, formed by postkinematic mimetic *lit-par-lit* replacement

schistosity and become directionless granite. Further west in the canyon, outcrops of this rock are well-exposed on the Burma Road, and contain completely undisturbed relics of paragneiss with feldspar porphyroblasts and granitized bands. These relics are excellent examples of what G. E. Goodspeed has termed "skialiths." Small veins of postkinematic replacement aplite are also often found in the Ts'angshan gneiss.

The local postkinematic granitization in the Ts'angshan gneisses is of particular interest because it is continuous with the synkinematic replacement in these rocks. The process of metasomatism had reached a climax during the later part of the period of orogenic deformation, and it still continued, although on a more local scale, when deformation ceased. It is therefore possible to compare the effects which the same

granitizing solutions have had on the same rocks under different mechanical conditions, i.e. (1) during differential deformation of the country rock, (2) at the time of waning deformation, and (3) after deformation had definitely ceased.

As to (1), the metamorphic migmatites thus formed show sharp parallelism of all their structures and well-marked *schistosity* which was *mechanically active* at the time of formation of these rocks. This "active schistosity" differs from *passively inherited relict schistosity* in its appearance as well as in the behavior of the component mineral grains (kind and degree of preferred orientation, combination of growth and deformation features). There is no need to illustrate examples of synkinematically metasomatized Ts'angshan gneisses, since their appearance is identical with that of the synkinematic gneisses of Nanga Parbat, and I may therefore refer to the illustrations in Part I.

Rocks metasomatized at the time of waning deformation are transitional in character. An example is shown in plate 2, figure 2. Parallelism of banding, and schistosity in the transformed layers, are less sharp than in rocks which were replaced under fully synkinematic conditions. A certain tendency of the metasomatizing solutions to spread in directions other than that of the schistosity of the country rock, becomes for the first time visible but still remains largely repressed. It might be objected that the rock shown in plate 2, figure 2, was granitized under entirely static conditions, that its banding was guided by the pre-existing schistosity of the country rock, and that the schistosity of the replaced portions is an inherited relict structure—a process which may be called "mimetic replacement." This process has undoubtedly taken place in many metamorphic migmatites, but I have nowhere seen rocks with mimetic replacement in which part of the metasomatizing solutions have not succeeded in "emancipating" themselves from guidance by the mechanically inactive older schistosity of the country rock, and in thus forming some cross-cutting contacts which interrupt the parallelism of mimetic replacement.

Figure 3 in plate 2 shows latest-kinematic replacement succeeded by early post-kinematic metasomatism. The former is similar to that shown in plate 2, figure 2, and the latter has formed small cross-cutting pegmatitic-aplitic veins. Their replacement origin is shown by gradations and by some inherited schistosity

which is chiefly marked by small relics of biotite-gneiss the biotite of which has usually been more coarsely recrystallized. The vein on the left still shows, on a very small scale, some mimetic guidance of replacement by the schistosity of the country rock, but as a whole this vein transects the schistosity. The continuous transition from syn- to post-kinematic metasomatism is obvious in this rock. A more advanced stage of post-kinematic replacement is illustrated by figure 4 in plate 2. Leucocratic granitic veins transect medium-grained biotite-flasergneiss in various directions, and are only very locally (center of figure) guided by its schistosity.

Small statically formed metasomatic veins and patches of the types shown in text figures 2 and 3 and in plate 2, figures 3 and 4, are common in the Ts'angshan gneisses. They are typical of those found in many other areas in which granitization has continued after the end of orogenic deformation. Similar patterns are frequently developed on a much larger scale. In fact, the detailed features which have been figured, are *diminutive models of patterns displayed on a regional scale in many granitized areas.*

III. RIVERSIDE-CONCONULLY AREA, NORTH CENTRAL WASHINGTON[4]

Some observations will be briefly presented which have a bearing on the questions treated in the present paper. This preliminary note will be followed by a fuller description elsewhere.

(a) *Outline of areal geology*

In the Riverside-Conconully area west of the Okanogan River, a thick geosynclinal Paleozoic succession has been intensely folded, variously metamorphosed, and in part granitized, presumably in Jurassic time. The lower part of the column consists of dolomites and limestones most of which have been altered to banded marbles. They conformably underlie rocks equivalent to parts of the "Anarchist series" established

[4] I studied this area when conducting the 1948 geologic field course of the University of Washington. The area is located southwest of the region in which Waters and Krauskopf have described the "Anarchist series" and the "Colville batholith" (1941). I wish to thank Aaron C. Waters for introducing me to this region during a joint field trip, in which Richard W. Lounsbury also participated. The latter assisted me during the field course; his Stanford Ph.D. thesis will deal with an area farther north.

by R. A. Daly (1912) near the border and extended to the south by A. C. Waters and K. Krauskopf (1941). Fossils locally preserved in the limestone indicate a Paleozoic and, according to a preliminary examination by H. E. Wheeler, probable Devonian, age. The upper part of the column consists chiefly of thick argillites altered to phyllites and biotite-schists, with actinolite-tremolite-schists and granulites in their lower part. Most of these latter were derived from impure dolomitic sediments, and grade laterally into amphibolites. Synorogenic regional metamorphism of varying degrees has been succeeded in wide parts by static thermal recrystallization. Typical examples are phyllitic biotite-schists containing large post-kinematic andalusite porphyroblasts. Many of the originally synkinematic schists show superposed hornfelsic textures.

The degree of metamorphism is clearly related to granitization which comprises a synkinematic and a postkinematic phase and thus matches the history of metamorphism. Granitized areas covering hundreds of square miles occur to the west and southwest. They contain relict zones of Paleozoic metamorphic rocks in which the predominantly northwesterly regional orogenic trend has been left undisturbed. These metamorphic rocks were still found in the high granitic Tiffany range[5] on the west which forms the divide between the Okanogan and the Methow valleys. A smaller granitized body, measuring about ten square miles, occurs within the sedimentary area west of Riverside.[6] It occupies the core of a syncline, replacing biotite-schists and amphibolitic rocks, whereas the underlying marbles which form the limbs of the syncline, have escaped granitization. Generally, in the Riverside-Conconully region, *the calcareous-dolomitic anticlines have not been granitized,*[7] *and granitization has been restricted to parts of the synclinal areas composed of the younger rocks which were chemically more susceptible to transformation.*

[5] A detailed study of this area is being carried out by R. Goldsmith for an advanced degree in geology at the University of Washington, whereas J. Robertson is doing a Master's thesis on the rocks near Conconully.

[6] A detailed study of the rocks in this granitized body is being made by L. T. Grose for a Master's degree at the University of Washington.

[7] In an area farther south, west of Omak, granites of mostly still undetermined origin contain marble remnants with high-temperature lime-silicates. This area is being studied by W. C. Boulton for an advanced degree.

(b) *Summary of synkinematic granitization*

Synkinematic metamorphic migmatites are developed in the western and southwestern portion of the area. In wide parts they have been subjected to subsequent static replacement and as a result they have partly lost their identity. The synkinematic gneisses closely resemble those described in Part I. There are feldspar-porphyroblast-gneisses, banded gneisses, augengneisses and flasergneisses. They have formed from biotite-schists and partly biotitized amphibolites, which often occur as relict bands in the gneisses, and grade into them. Metasomatic feldspar porphyroblasts exhibit the usual replacement features. Structural parallelism is general in the synkinematic gneisses.

Massive granitic-appearing biotite-augengneisses are for instance typically developed south-southeast of Conconully. They occur near the border of the granitic area, and locally include relics of sillimanite-schist. Farther west, a complete transition from lime-silicate-schist into banded gneiss and flasergneiss was observed, with intervening stages of amphibolite and feldspathized amphibolite. In the high Tiffany range on the northwest wide areas of synkinematic migmatitic gneisses with relict bands of biotite-schists and amphibolites were found to occur as far as 11 miles west of the border of the granitic mass forming this range. They demonstrate that metasomatic replacement was not restricted to the marginal parts of this mass, but was responsible for the formation of its central portion as well, i.e. that granitization was of batholithic dimension.[8] Some amphibolites run from the non-granitized eastern region into the western granitic area and can be traced to the summit of the high Tiffany range.

Most of the synkinematically granitized rocks have textures which indicate that their crystallization lasted longer than their deformation. In view of the widespread postkinematic continuation of granitization in this region, it is not surprising that even those rocks which were not directly affected by the postkinematic phase of replacement, generally remained hot enough to continue their recrystallization for some time.

(c) *Summary of postkinematic granitization*

The static phase of granitization in this area is characterized by crosscutting contacts and by predominantly direction-

[8] I have seen similar conditions east of the Okanogan Valley.

less granular fabrics. At many places, it has transgressed the limits of synkinematic granitization. We may therefore distinguish between static replacement (1) in synkinematic gneisses, and (2) in previously non-metasomatized metamorphics. On the basis of the size of individual replacement bodies, we may differentiate into static granitization (a) restricted to small-scale features, and (b) responsible for the formation of larger "eugranitic" bodies.

Case (1a) shows impregnation of synkinematic gneisses with small replacement veins and patches which have crosscutting and irregular contacts and sometimes have preserved relict schistosity. These small replacement bodies closely resemble those described above from Ts'angshan, and there is the same continuous structural evolution from synkinematic to postkinematic forms of replacement. I refer to the description in chapter II, and to figures 2-4 in plate 2 all of which might have been photographed in the present area. These features are, for instance, typically developed in part of the Tiffany range on the west of the area. Here metasomatic formation of postkinematic pegmatites is well displayed. Large pink potash-feldspar idioblasts began to grow in the gneiss, concentrated in small groups, and finally coalesced with the coarsely recrystallized remnants of the gneiss into patches and veins of pegmatite.

Case (2a), i.e. small-scale static granitization in previously non-granitized rocks, is represented by chiefly aplitic irregular veins and patches. There are all gradations into the country rocks which are mainly biotite-schists and amphibolites, the latter frequently biotitized. As a whole, preservation of relict schistosity is rare. Part of the enclosing schists have a superposed hornfelsic texture. Relics of schist are common in the small replacement bodies, and do not show any signs of disturbance, not even where they form thin delicate lenticles and septa which have preserved the direction of schistosity of the country rock within replacement dikes. Good examples are exposed northeast of Conconully. Here and at other localities, also occur true dilation dikes[9] of aplite. I would attribute them to mobilization and intrusive movement of granitized material, rather than to intrusion of original gran-

[9] As to criteria for "dilation dikes" and "replacement dikes," I refer to G. E. Goodspeed (1940).

itic magma.[10] At the locality northeast of Conconully, even barely granitized biotite-schist has, in the form of a cross-cutting dilation dike, intruded biotite-schist.

Apart from the small-scale and incipient features described, static granitization has in this area produced larger bodies of "eugranitic" rocks, in areas of synkinematic gneisses as well as of previously not granitized metamorphics (cases 1b and 2b). The rocks are predominantly dioritic, quartz-dioritic, trondjhemitic and granodioritic though granitic varieties also occur.[11] These rocks usually lack relict schistosity. Their texture is crystalloblastic and frequently porphyroblastic. Most of the rocks have an even-granular overall appearance, others look porphyritic, often owing to the presence of late potash-feldspar porphyroblasts. Contacts are mostly, but not always, transitional. More fine-grained and basic relics of country rocks are extremely common and show all stages of transformation. In spite of their mostly rather uniform overall appearance, the rocks generally look patchy and uneven in detail where well exposed, often with slightly darker shadow-like areas which to some extent are due to variations in texture, but chiefly in composition, especially in the amount of mafics. I would attribute all these heterogeneities to replacement origin. Microscopic clusters of mafics suggest recrystallized remnants of country rock.

The features described occur in the western areas, for instance in a large chiefly quartz-dioritic and tronhjemitic mass on the eastern slope of the high Tiffany range, as well as farther east, beyond the eastern border of the region affected by synkinematic granitization. North of Conconully near the eastern border of the main area of granitization, relict inclusions, replacement breccias, and granitized patches resembling the "small granodioritic blocks" described by G. E. Goodspeed (1937) from Oregon, occur together, with all transitions from the country rocks through porphyroblastic to "eugranitic" rocks. Here and at several other places, schistose and more compact amphibolites have been successively transformed into gabbroid, dioritic, and quartz-dioritic rocks; where potash

[10] References to the ideas of several authors on "diapirites," "migma," "rheomorphism," "neomagma." are given below in chapter IV.

[11] Southeast of the region here described, a large area of leucocratic granite occurs near Omak. Its origin is still undetermined.

introduction has led to the formation of frequently porphyroblastic potash-feldspar, the granodioritic stage has been reached.

Smaller granitized bodies occur still farther east in the metamorphic Paleozoic rocks, and a somewhat larger quartz-dioritic and granodioritic mass occupies a synclinal core west of Riverside (cf. above). It exhibits the replacement features mentioned above. Some relict lenses of amphibolite and biotite-schist can still be correlated to the normal stratigraphic sequence in the syncline. The amphibolite is a more highly metamorphic facies of the actinolite-tremolite rocks mentioned above, and grades into gabbroid-dioritic rocks. Apart from the directionless granular rocks, gneissic rocks occur more locally. Most of them are augengneisses containing varying amounts of potash-feldspar porphyroblasts. They grade into directionless porphyritic-appearing granodioritic rocks with the same porphyroblasts. Apart from the nature of the granitized rocks and their relations to the metamorphic sediments, the fact that the calcareous-dolomitic limbs of the syncline have not been affected, in itself suggests metasomatic replacement of selective character.

Whether the larger statically granitized bodies in this region have to some extent been affected by "rheomorphic" processes (cf. below, chapter IV), is difficult to decide without further detailed study. However, most of these rocks have not undergone mass movement, but remain where they were formed through metasomatic processes.

IV. DISCUSSION OF GENETIC RELATIONSHIPS OF SYNKINEMATIC AND STATIC GRANITIZATION[12]

(a) *Criteria for synkinematic and static crystallization and granitization*

Since sometimes *all* granitization is treated as a static process, it appears appropriate to summarize briefly the *criteria for synkinematic crystallization and granitization* of the type described in Part I. The higher grades of regional metamorphism in geosynclines were in Part I found to be

[12] The general discussion in this chapter is based on the rocks described in Parts I and II, and in the first three chapters of Part III. In order to avoid tedious repetition, reference to those descriptions is made only in a few cases.

intimately linked with granitization and to depend on it for a supply of additional heat. Therefore, evidence of synkinematic crystallization in higher grade metamorphic rocks is also evidence of a synkinematic character of metasomatism in associated granitized rocks. In fact, in non-granitized and granitized rocks occurring together, crystallization differs only insofar as in the latter, in addition to substances of the original rocks, introduced material has participated. Therefore, both groups of rocks show essentially similar structural features indicative of synkinematic origin. Main field criteria are: well-developed schistosity and a general sharp parallelism of such elements as bands, stringers of porphyroblasts, etc., and an absence of crosscutting relationships—features which are typically developed at Nanga Parbat as well as in many other areas.

Microscopic criteria are numerous. Many of them have been described for regionally metamorphosed rocks in B. Sander's fundamental treatise on metamorphic fabrics (1930, pp. 262-275). Similar features are often found in synkinematically granitized rocks like those of Nanga Parbat. General criteria for synkinematic crystallization include: "snow ball garnets" and other porphyroblasts rotated during growth; the occurrence, in the same thin section, of folds composed of deformed minerals such as micas, and of other folds consisting of undeformed micas in polygonal arrangement ("polygonal arcs"); the presence of polygonally arranged, undeformed, and of folded micas in different parts of the same microscopic fold; the superposition of slight folding in a polygonal arc, both mechanical bending and polygonal arrangement representing the same pattern of deformation; fracturing and subsequent healing of crystals which may result in elongation parallel to the schistosity; generally speaking, the frequent occurrence of several overlapping successive submaxima both of deformation and crystallization, which can be individually dated by certain mineral species (one species sometimes having more than one maximum of crystallization); thus detailed time analysis is possible, and, as a whole, one continuous major process consisting both of deformation and crystallization is indicated. Furthermore, the common metamorphic structure termed "crystallization foliation" (well-developed schistosity without mechanical disturbance of crystal

lattices) is rarely due to entirely static mimetic crystallization; under static conditions usually some transversely oriented crystals develop, and if mimetic granitization is added, invariably cross-cutting contacts also form. Typical crystallization foliation may rather be considered as the result of crystallization which was mainly synkinematic and was able to heal lattice disturbances caused by contemporaneous deformation, and which usually lasted somewhat longer than deformation so that any remaining lattice disturbances were eliminated. Additional criteria common in synkinematically granitized rocks are elongation and parallel alignment of metasomatically formed feldspar porphyroblasts and parallelism of replacement bands, apart from frequent traces of mechanical deformation in porphyroblasts which may or may not have been healed by continuing crystallization.

Static crystallization and granitization are free from contemporaneous deformation of the rocks involved. The term "postkinematic" refers to a static process succeeding a phase of differential deformation which may also have been a phase of synkinematic granitization. Except at great depths, static recrystallization of sediments requires introduction of heat,[13] and as I have tried to show in Part II this heat in areas of static granitization is transported by the granitizing agent. Accordingly, the thermal recrystallization of sedimentary areas adjacent to granitized bodies is traditionally included with contact metamorphism.[14] Static crystallization in nongranitized and granitized rocks differs only insofar as in the latter introduced material participates in addition to the substances of the country rock. Both groups of rocks typically have a directionless fabric, lacking schistosity unless it has been inherited as a relic. Previously unmetamorphosed sediments, if thoroughly recrystallized, develop hornfelsic fabrics, with mineral associations varying according to temperature. Bedding is frequently preserved, in the form of differently colored layers differing in composition, and sometimes of division planes. Contrary to some statements in the literature, I have not seen a single case in which bedding in statically

[13] This is confirmed by the preservation in many geosynclines of completely unmetamorphosed sediments five to ten miles thick and sometimes even thicker.

[14] I would restrict the term *contact metamorphism* to thermal metamorphism at true igneous contacts.

recrystallized sediments has become schistosity. The fundamental contrast between a hornfels and a schist[15] illustrates this point. Crystalline schists are not made without differential rock deformation.

Statically granitized rocks are directionless[16] unless they have inherited relict schistosity. In granitized sediments, bedding sometimes survives as a usually faint relict structure, but (contrary to some statements in the literature) it does not become gneissic structure—all products of static granitization of non-schistose sediments I have seen, have directionless fabrics. Characteristic of static granitization are irregular and crosscutting contacts which transect the bedding or the schistosity of the country rock. Granitized patches in the country rock and relics of the latter in the granitized rock, show irregular shapes and are irregularly scattered. Statically granitized rocks and statically recrystallized sediments both have crystalloblastic textures and both lack structures indicative of contemporaneous differential deformation, but the granitized rocks contain metasomatically formed porphyroblasts and have a larger average grain size. Transitional textures are common. Textural and mineralogical relics of the country rocks are widely preserved in the granitized rocks (cf. Part II). At advanced stages of transformation, metamorphic features, such as porphyroblastic textures, usually become less conspicuous, and the textures more igneous-appearing.

Where the rocks subjected to static granitization have been low-grade crystalline schists (phyllites, greenschists, etc.), and, near granitized bodies, have undergone static recrystallization at medium or high temperatures, they tend to approach hornfelsic fabrics, rather than to become typical medium- or high-grade crystalline schists. Lack of stress and deformation during recrystallization may also have its mineralogical expression, as in the synkinematic biotite-phyllites west of Riverside (chapter III) in which andalusite formed when static granitization took place in the vicinity. In granitized rocks of

[15] In addition to the differences in structures and textures, there are a few mineralogical differences. Kyanite is synkinematic, andulasite static; almandite is much more common in synkinematic rocks, etc.

[16] Possible later flow structure due to mass movement of metasomatized rocks, e.g. "rheomorphism" as defined by G. E. Goodspeed (1949), belongs in a different genetic category.

this group, little of the schistosity of the original low-grade schists survives; the rocks are mostly directionless.

Where the country rocks are medium- and high-grade crystalline schists and synkinematically metasomatized gneisses, i.e. rocks already adapted to higher temperatures, in most cases little change is visible near statically granitized bodies, though there may be a certain tendency to superpose, on the schistose fabric, some hornfelsic or directionless-granulitic features (chapter III). This tendency is often recognizable in thin sections only. In statically granitized rocks of this derivation, the schistosity of the country rocks frequently survives as a relict structure ("mimetic granitization"), but it usually becomes increasingly faint as the process of static metasomatism progresses. Finally, it is lost, and the granitized rock becomes directionless. In other cases, the schistosity of the country rock is lost during an early stage of static metasomatism. As a whole, small replacement bodies more often retain relict schistosity than large ones. The best criterion for a static origin of replacement bodies retaining relict schistosity, is irregular and crosscutting contacts. Microscopic criteria include absence of structures indicative of active deformation, and lack of directional control in the spreading-out of metasomatic feldspar porphyroblasts.

In most cases where synkinematic is succeeded by static granitization, both are merely successive phases in a continuous process. Examples have been described in chapters II and III. Relations between these phases are characterized by transitions, and the contrasting critical features discussed above gradually replace each other. The relative extent and degree of each of the two phases of granitization varies in different areas. The postkinematic phase may be restricted to small-scale features (chapter II, Ts'angshan). Or it may form large bodies and even spread far beyond the limits of the synkinematic phase (chapter III, Riverside). In some cases, the static phase does not occur in immediate continuity with the synkinematic phase, but seems to represent a renewed upward surge of the granitizing agent after it had already subsided. Examples are the postorogenic granitic bodies in the Nanga Parbat gneisses (chapter Ia), in which, incidentally, no relict schistosity was observed.

Can the static processes, *mimetic crystallization* and *mimetic*

granitization, make rocks which are indistinguishable from those of synkinematic origin? First, it must be realized that crystallization described as "post-tectonic" is in numerous cases crystallization which was chiefly syntectonic and merely lasted somewhat longer than deformation. Examples are strong crystallization foliation as interpreted above, or, to mention a specific feature, such polygonal arcs which must be interpreted in a similar way on the strength of other structural features in the same rock. An example among granitized rocks is the gneiss in the interior of the Nanga Parbat massif which bears evidence of synkinematic origin though its crystallization lasted somewhat longer than its deformation—which, significantly, did not lead to the formation of any crosscutting replacement veins. Contrasted to all these cases is mimetic crystallization as an entirely postkinematic or static process. Its products do not possess the same sharp structural parallelism as those of synkinematic crystallization. Even if a majority of the grains are guided in their growth by the inherited schistosity, yet there are usually others which ignore it, namely transverse crystals and porphyroblasts. The same applies to an altogether static mimetic granitization. Relict schistosity may be preserved, but it becomes successively fainter during the process. It is in most cases marked by inherited mafics whereas the feldspar porphyroblasts tend to ignore it. Contacts of granitized portions may partly follow the pre-existent schistosity of the country rock, but crosscutting and irregular patchy contacts invariably *also* develop (text figs. 2 and 3; pl. 2, fig. 3).

(b) *Genetic relationships of synkinematic and static granitization in geosynclinal belts*

It is generally agreed that the *geosynclinal type of orogeny*[17] is characterized by intense folding frequently accompanied by large-scale thrusting. Equally characteristic of geosynclinal belts of first order (eugeosynclines[18]) are *regional metamorphism*

[17] The term "geosyncline" is used in its restricted sense ("true geosynclines" of H. Stille, 1924; "mobile belts" of W. H. Bucher, 1933; "orthogeosynclines" of Stille, 1940, and of M. Kay, 1944), excluding basins in more stable regions ("parageosynclines" of Stille, 1940; "monogeosynclines" etc. of Kay, 1944). "Orogeny of geosynclinal type" then is equivalent to Stille's "alpinotype orogeny" (1924)—a term which was never intended to set up the Alps, with their extreme degree of nappe structure, as a standard.

and granitization. Indeed, it may be said of first order geosynclines that the beautiful sections of folded and overthrust fossiliferous sediments which figure so prominently in our concepts of geosynclinal mountains, are only a superficial skin and marginal zones, compared with the deeper and central portions of the geosynclinal body where compressive structure is coupled with even more fundamental transformation brought about by metamorphism and granitization. Folded geosynclines which lack this profound transformation, are of second order (miogeosynclines[18]), and it is more than coincidence that nearly all of them also lack another sign of mobility of highest degree, namely the welling-up of sima-born basic magma during their time of subsidence and sedimentation.

Where in the inner portions of eugeosynclines the mechanical forces of orogeny act most strongly and the rocks suffer intense differential deformation, *dynamic regional metamorphism* results. However, if the analysis in Part I, chapter IV, is correct, this process makes *only lower-grade crystalline schists* (cf. definition of dynamic metamorphism in footnote no. 2, p. 681) and, except at very great depths, *higher-grade schists* form only where *additional heat* is supplied by the *agent of granitization.* This agent *combines chemical with thermal action.* Both are required to granitize, whereas the latter, where acting alone, results in *higher-grade regional metamorphism,* which thus is a *byproduct of granitization.* The most fundamental transformations which occur during orogeny in eugeosynclines, are thus due to the chemical and thermal action of the granitizing agent.

Mechanical deformation and chemical-thermal action present themselves as different aspects of one major geological phenomenon, i.e. eugeosynclinal orogeny, and a close genetic relationship must exist between them. For not only is granitization confined to eugeosynclinal zones (as can be demonstrated at least for post-Archaean time), but also it is entirely absent during the pre-orogenic period of geosynclinal subsidence when sima-born basic volcanism has the stage. Obviously, granitiza-

[18] Stille (1940) has divided orthogeosynclines into "eugeosynclines" and "miogeosynclines" and Kay (1944) has adopted a similar classification. Eugeosynclines have basic volcanism during their period of subsidence ("initial volcanism" of Stille, 1940), miogeosynclines do not. This criterion in most cases coincides with that of presence or lack of metamorphism and granitization.

tion is either a direct consequence of orogeny, or it is itself an integral process at the root of orogeny. Like granitization, regional metamorphism of low as well as of high grade does not seem to occur in pre-orogenic time. The hypothesis that during the time of subsidence "geosynclinal metamorphism" or "load metamorphism" can be produced statically by load and geothermal increase of temperature, can hardly be reconciled with the numerous sections of completely non-metamorphic geosynclinal rocks five and ten miles thick.

Static granitization occurs in the same environment as synkinematic granitization, i.e. in eugeosynclinal belts. It does not occur unless strong orogeny has previously taken place. It thus appears to be *genetically linked with orogeny*, although it is later and therefore static. Its connection with a previous period of orogeny is further emphasized by the fact that it has commonly been preceded by synkinematic granitization in the same general area. In fact, in numerous regions static granitization is merely *the continuation, after the end of orogeny, of a process begun during orogeny*. A continuous evolution of structural forms of metasomatic replacement is characteristic. Typical cases have been described in chapters II and III, and many others could be added. In some other areas, there is a certain discontinuity between synkinematic and static granitization, indicating postorogenic subsiding and subsequent new rise of the front of granitization (cf. chapter Ia).

There are also *regions in which only static granitization is exposed*. In Part II, a case has been described where synkinematic granitization is absent not only in the immediate area of static granitization, but where in a much wider region synorogenic alteration has not gone beyond low-grade (dynamic) metamorphism. The question is whether in such cases there really has been no synkinematic granitization at all prior to static granitization, or whether it is merely concealed at depth. The second alternative seems to have much in its favor. As has been stated above, static granitization has frequently been preceded in the same area by synorogenic granitization, and always by orogeny. It therefore appears that orogeny and the birth of granitization are genetically linked. Moreover, static granitization has frequently spread beyond the limits reached by synkinematic granitization in the same area, and it is plausible that it has done so not only laterally but, to an

even larger extent, vertically. For after the end of orogeny, mechanical conditions favor a *further rise of granitizing emanations*. The compressive stresses of orogeny have then disappeared, and general uplift in the geosynclinal belt tends somewhat to loosen the cohesion of the rocks.

That in postorogenic time the granitizing agent may actually penetrate higher levels than during orogeny, is proven by *cases of static granitization "at unusually shallow depth"* (cf. Part II). The contrast between more deep-seated and shallow static granitization is to a large extent responsible for the textural variability of the products of static granitization which, as a whole, is greater than in synkinematically granitized rocks all of which converge toward granitic gneiss,[19] whereas some products of shallow static granitization never reach the eugranitic-appearing stage even if their chemical alteration has been very thorough. Where static granitization can stratigraphically (and texturally) be demonstrated to have occurred at a very shallow depth, no synkinematically granitized rocks are visible. This is hardly a coincidence. In such cases, the synkinematic gneisses are probably concealed at greater depth. Where synkinematic and static granitization are exposed in the same area, the latter does not belong to the variety characteristic of very shallow depth. Where static granitization does not belong to that variety either, and where yet no synkinematic gneisses are exposed, they may be supposed to be present in the deeper portions of the geosynclinal belt although there is, of course, no proof.

The sizes of synkinematically granitized bodies known to me are all fairly large. At least, I have never encountered small and isolated patches of synkinematic gneisses. The process acts on a regional scale, and frequently reaches the dimensions of large batholiths (cf. Part I). *The sizes of individual statically granitized bodies* vary greatly (cf. Part III, chapters I to III). Very small bodies are common, though there are usually a number of them scattered in the same general area. Larger bodies are equally common, and frequently reach the dimensions of large batholiths. I think that *the majority of the large granodioritic and granitic batholiths have most*

[19] Contemporaneous differential deformation is another factor which tends to make the fabrics of synkinematic gneisses more uniform, being unfavorable to the preservation of pre-existing grain textures.

probably formed by metasomatic granitization. Apart from the growing body of regional evidence for granitization, which the workers in this field are contributing in different parts of the world, certain general considerations seem to favor a metasomatic as against an igneous intrusive origin. Such arguments have been advanced by several authors; I refer to the recent reviews by H. H. Read (1943, 1944, 1948). These arguments include the room problem which is linked with the usual lack of signs of displacement of the country rocks near large batholiths; and the great predominance of granitic over basic rocks within the crust, in contrast to the even greater predominance of basalt and related rocks among the volcanic rocks—an argument which is strengthened by definite evidence of simatic origin found in some basalts. I would add another argument. It seems difficult to conceive of enormous masses of granitic igneous magma rising to shallow levels in the crust, in broad fronts extending over tens of thousands of square miles, without breaking through to the surface. If the large granitic batholiths were igneous, I should expect that those geosynclinal belts in which they occur, would in postorogenic time have been drowned in floods of rhyolites, dacites, and related rocks.

True igneous granitic bodies where an intrusive mechanism can be demonstrated and a genuine igneous texture is developed, are usually comparatively small. They may occur far away from areas of granitization and are, in fact, not restricted to eugeosynclinal belts. In other cases, *intrusive granitic bodies* occur *in areas of granitization* where they are often restricted to small-scale features such as dikes (cf. Part III, chapter III). Such cases may be interpreted as an advanced stage of granitization during which metasomatized material became finally mobilized and was thus able to intrude. This idea has been suggested by a number of authors. J. J. Sederholm (1926, p. 135) wrote of "anatexis" and "palingenetic (i.e. re-born) magma," implying essentially a process of re-fusion. C. E. Wegman (1930; 1935, pp. 334-335) uses the term "diapirite" for large masses of migmatitic material which plastically flowed and became intrusive. M. Reinhard (1935) speaks of "migma," i.e. mobilized migmatitic material which consists of a mixture of solid and liquid and might intrude like magma. H. G. Backlund (1937, p. 234) uses the term "rheomorphism"

for partial or complete liquification of metasomatized rocks which then might act like magma. G. E. Goodspeed (1939, p. 399) speaks of "neomagma," i.e. locally newly formed magmatic material of metamorphic origin which performs a mass movement of plastic flow. He (1948, pp. 72-73; 1949) defines "rheomorphism" as mass movement of material of metamorphic derivation, and presents evidence in the form of "rheomorphic dikes."

The principle of mobilization and intrusive movement of material of metamorphic derivation does not necessarily imply whether the material is a plastic crystalline rock, a crystal mesh with subordinate interstitial liquid, a melt-solution, or a mixture of the two latter. Probably these cases all occur. That plastic crystalline rock is capable of local intrusive movement, even without having necessarily been granitized, has been mentioned in chapter III (p. 690). So far, rheomorphism has been definitely demonstrated only on a small scale (Goodspeed, 1949). It seems probable that generally intrusive bodies of rheomorphic origin are relatively small, compared with the size of large batholithic masses formed by metasomatism in situ. However, much field work still remains to be done.

As stated above, granitization comprises both *chemical and thermal action.* The latter involves introduction of heat conveyed by the mobile agent which infiltrates and granitizes the geosynclinal rocks (cf. Parts I and II). Except at very great depths, introduction of heat is required for regional granitization as well as for regional recrystallization in high-grade mineral facies. Probably additional heat is generated in situ by exothermic reactions (cf. V. M. Goldschmidt, 1921, p. 135; J. A. W. Bugge, 1945, p. 15), *after* higher temperatures have been attained. The *primary* source of heat is obviously from below. "From below" implies from depths greater than are exposed anywhere, i.e. exceeding 15 to 20 miles. Moreover, the source of heat must be at least as deep as the place of origin of the critical elements carried upward by the granitizing agent. I shall try to show that the added alkali originates not only beneath the geosynclinal prism, but most probably even beneath the lower boundary of the sial zone. The primary source of the heat required to granitize the inner zones of eugeosynclines, thus appears to be at very great depth. The time when this heat is generated beneath geosynclines and

rises into them, is that of orogeny; for orogeny and birth of granitization are contemporaneous and genetically linked (cf. above). The question whether orogeny is responsible for generation of the heat, or whether both are consequences of something else, or whether generation of heat is a primary cause, leads into the realm of speculation. Perhaps geophysical, and especially seismic, methods may help to solve this question.

Chemical action involved in granitization includes both an *addition* of certain substances to the geosynclinal body, and *redistribution* of some of the material contained in it. We may speak of a "metabolism of geosynclines." Redistribution implies mobilization, transfer, and re-precipitation. Various elements may be so affected (including rarer ones). They will frequently, though not necessarily, be excess substances in rocks undergoing granitization ("excess" relative to a granitic composition).

Next to the alkalies, *silica* is the substance most frequently precipitated during granitization. Though part of the sediments in geosynclines have sufficient or excess silica, the granitization of many geosynclinal sediments and nearly all geosynclinal volcanic rocks requires additional silica, often in considerable amounts (cf. Part II, chapter IVe). A large amount of silica will usually be provided by transfer from silica-excess sediments, but it appears very likely that additional silica is introduced from beneath the geosynclinal prism. This is suggested by the fact that the granitizing agent has in most cases been able to satisfy the needs of silica-deficient rocks, irrespective of the composition of the geosynclinal column in individual areas. Also, in some regions quartzitic members have escaped granitization and thus kept their excess silica. Granitization of siliceous rocks obviously requires mobilization and transfer of some of the abundant aluminum of geosynclines.

The most important material added is *alkali* (cf. Parts I and II). The considerable amounts of alkali consumed in regional granitization could not be supplied by mere redistribution of the alkali originally contained in the geosynclinal rocks. For as a whole the geosynclinal column is alkali-deficient in comparison to granitic rocks, and there is no evidence of a regional loss of alkali in the non-granitized portions of geosynclinal bodies. Moreover, among sediments alkali is chiefly contained

in argillaceous rocks, in which potash exceeds sodium. Therefore, even if the total alkali-deficiency is ignored, the contrast between regional sodium and potash metasomatism could not be accounted for. The only sediments very rich in alkali are salt deposits. Could they have supplied the alkali required for granitization? Theoretically, this might be possible in exceptional cases though no supporting field data are known. As a general solution, this hypothesis fails. There are not enough salt deposits, and in geosynclines they are less common than in non-geosynclinal basins, and in a number of cases entirely absent. Moreover, cases of strongly potash-predominant metasomatism could not be explained, in view of the scarcity of potash salts in salt deposits.

It follows that most of the alkali which is added during granitization, has come *from beneath the geosynclinal prism.* Could it have been derived from the gneissic and granitic pre-geosynclinal basement rocks? This appears unlikely. There would be required a process of "de-granitization" of the basement; for it would have to give off a considerable part of its alkalies (and probably some of its silica) in order to make into granitic rock the overlying geosynclinal prism deficient in alkali. Melting of the basement would not solve the difficulty, since it would merely result in mobilization and rise of granitic material, but could not create an agent sufficiently enriched in alkali to perform regional granitization of alkali-deficient rock masses. As to observed facts—quite apart from the question whether *all* eugeosynclines do have old granitic basements *throughout* their inner portions—the granitic basement has remained granitic wherever it is actually visible in eugeosynclines, which is partly in their inner and more often in their outer zones.

It must be concluded that the alkali added to the geosynclinal prism has come *from non-exposed depths*, and probably from beneath the granitic or sial zone. P. Eskola (1932; 1933) suggests that granitic magma may form by *selective* re-fusion of rocks in the sima zone, through formation of a granitic pore magma which is squeezed out and rises into the geosynclinal belts. This revolutionary idea of a selective mobilization might perhaps be somewhat modified, by assuming a comparable process, which, instead of selective remelting, might consist of selective mobilization of ions and molecules and thus

produce an alkali-rich mobile phase, some kind of emanation which by means of infiltration, permeation, and diffusion would rise into the geosynclinal prism and perform metasomatic granitization. Granitic magma rising into the geosyncline could intrude, inject, and locally metasomatize, but it would not be chemically capable of supplying the large amounts of alkali which are consumed in large-scale regional metasomatic granitization. C. E. Wegmann (1935, pp. 346-347) suggests that deep-seated melts considered to be the source of the substances added during granitization, might be of an alkaline type and, when intruding geosynclinal rocks, give off alkali, thus cause migmatization and themselves become calc-alkaline. This idea might be modified by assuming that rocks of an alkali-basaltic composition are common in the upper part of the sima zone, and that such rocks would, as a result of selective mobilization, give off alkali-rich emanations. Tempting though this idea is, there appears to be a major difficulty. The basic volcanic rocks of deep origin which are so characteristic of the preorogenic period of eugeosynclines, are mostly *not* alkaline, nor can they have been and lost alkali to the geosynclinal sediments, since at the time of basic geosynclinal volcanism no granitization and no regional alkali-metasomatism are known to occur.

Whatever ideas may develop as to the origin of the agent of granitization, a few things seem to emerge from the realm of speculation into that of fact, namely *that the majority of large granitic batholiths appear to be of metasomatic origin; that no magmatic source of the agent of large-scale regional granitization is visible within the depths exposed; that the birth of granitization is genetically connected with eugeosynclinal orogeny; that its primary motor is at great depth.* In this sense, *synkinematic granitization is the original process and static granitization a more secondary consequence, although it is able to rise to higher levels than are generally reached by synkinematic granitization.*

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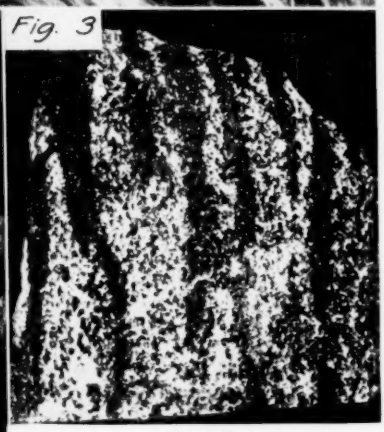

PLATE 1

Fig. 1. Postkinematic white tourmaline-granite in synkinematic darker granitic biotite-gneiss. East face of Gunar Peak (17,520′) northwest of Nanga Parbat, Northwest Himalayas. The face is about 5000′ high. After Misch (1935), Bild 42.

Fig. 2. Small replacement dike of white tourmaline-granite in synkinematic granitic biotite-gneiss. Lower border is irregularly sutured, upper border is fracture-controlled and sharp. East side of Buldar Ridge north-northeast of Nanga Parbat (no. 31.7.8). About natural size.

Fig. 3. Replacement hornblende-quartz-diorite in weakly schistose hornfelsic amphibolite. Metanorite mass northwest of Nanga Parbat gneiss massif. North of Gor Pass, north of Indus R. (no. 29.5.9). About ⅔ natural size.

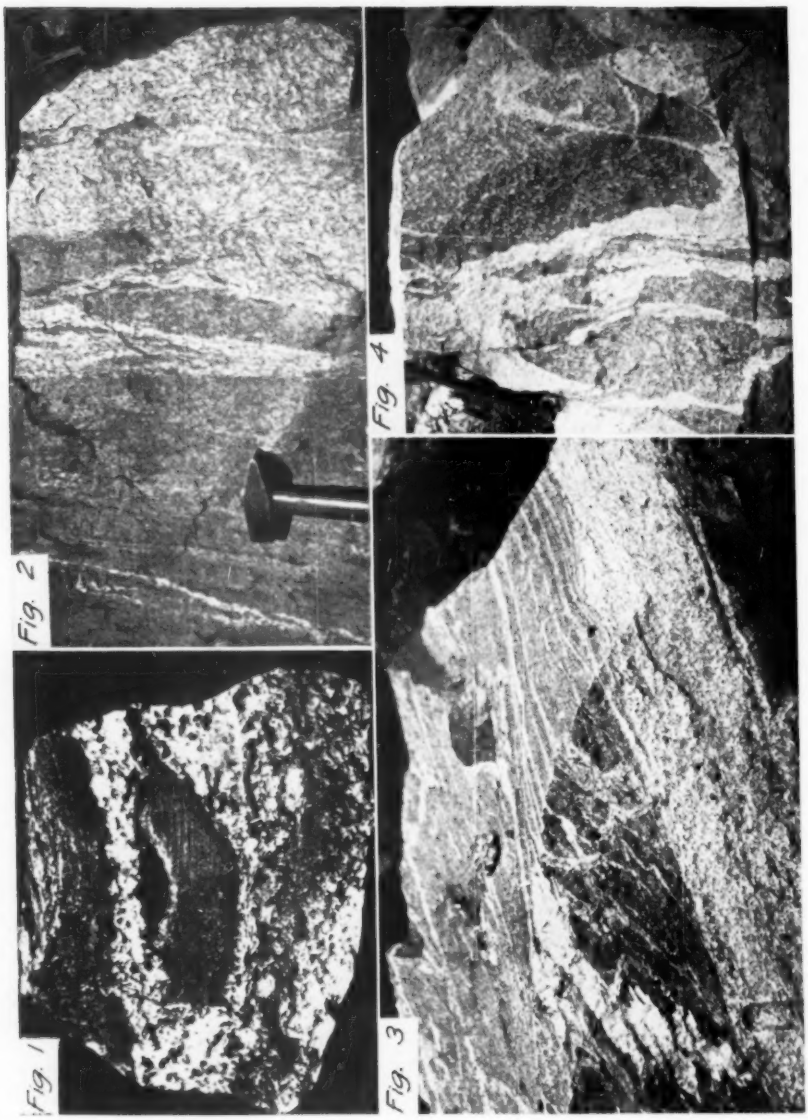

PLATE 2

Fig. 1. Replacement granodiorite in fine-grained compact hornfelsic amphibolite. Metanorite mass east of Nanga Parbat gneiss massif. West part of Kushnat Mountains southeast of Astor (no. 6.8.34). About ⅔ natural size.

Figs. 2-4. Postkinematic succeeding synkinematic granitization in Archaean gneiss of Ts'angshan, West Yunnan, Burma Road southwest of Hsiakuan (Erho Canyon).

Fig. 2. Transition from synkinematic to postkinematic phase.

Fig. 3. Late-kinematic succeeded by early-postkinematic replacement.

Fig. 4. Postkinematic phase of replacement.

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Department of Geology
University of Washington
Seattle, Wash.

ORIGIN OF PIMPLE MOUNDS

E. L. KRINITZSKY

ABSTRACT. Pimple mounds are remains of dunes and hillocks which have formed under a wide variety of conditions. These include environments of glacial outwash, coastal sand flats, and sandy point bars of meandering streams.

I. Introduction

PIMPLE mounds of various areas, and differing names, exist in great abundance. Along the Gulf Coast of eastern Texas and southwestern Louisiana they are best known and are numbered by the hundreds of thousands. Also they are plentiful in southeastern Missouri, western Washington, and parts of Iowa, to mention but a few regional areas.

Much has been written on the subject of these interesting features, but authors in the past have limited their studies to restricted areas. Thus there have been developed theories of origin which are based on purely local evidence and which become inadequate when applied to identical forms elsewhere. Without doubt, pimples may have a variety of possible origins only a few of which are of widespread importance.

The writer hopes to demonstrate a principle of pimple mound origin which has wide application but which, up to now, has not been advocated.

II. Origin of Pimple Mounds

A. Description

Typical pimples generally have the appearance of low, flattened domes which are either rudely circular or elliptical in horizontal cross-section. Often they coalesce and are ridge-like in appearance. Their basal diameters vary between ten and over a hundred feet and their height ranges from less than one foot to over five feet. In general, pimples of the Gulf Coastal Plain average between 35 and 50 feet in diameter and two or three feet in height. In all areas where these mounds occur, they are in extreme abundance and occupy large percentages of the land surface. Isolated individual mounds are very seldom found.

In the Gulf Coastal region, the material of which these mounds are composed is commonly a fine to sandy loam which is coarser than, and entirely distinct from, surrounding soils.

In Washington (Dalquest and Scheffer, 1942) the mounds are of a black graveliferous silt situated on a stratified, yellowish graveliferous alluvium deposited by glacial outwash. In portions of Missouri and Arkansas the mounds are composed of coarse loam in areas of distinctly finer soils.

Fossils or artifacts are hardly ever found in these hillocks.

B. MEANDER BELT PIMPLE MOUNDS

In plate 1 there is shown the appearance of typical pimples situated on Recent alluvial deposits in the Advance lowland near Cape Girardeau, Mo. It can be seen from the still distinct river scars that this entire surface has been reworked by a meandering stream which has since migrated away from the area. Typical meander bends, swales, and accretion topography on point bars are easily distinguished. And, associated with these features, are pimples oriented in patterns which are entirely conformable to the accretion ridges developed on point bars of the meandering stream.

The above conformity of pimples to meander belt topography is by no means unique. Similar situations are found in many areas. Typical examples occur in the Red River valley in Oklahoma and Texas, and in flood plain areas of Arkansas and Tennessee.

Accretion ridges on growing point bars along much of the lower Mississippi River are typically sandy, as are many towheads. These are sculptured by river currents during high water, built up as a result of accretion during falling water, and left exposed when lower water levels are reached. Since these accretions are periodic and occur generally after intervals during which the river bends have been migrating, most sandy accretion ridges are separate and distinct. Between these accretion ridges are the so-called swales which develop luxuriant growths of willows and trap fine sediments when flooded during times of high water. Thus the topography contains very gentle swells of coarse sediments protruding from areas filled with finer alluvium. In very short order, mantles of vegetation creep onto these sediments and develop soil profiles into them. To a great extent, vegetation aids in preserving certain of the topographic configurations. With removal of this covering by agriculture, many meander belt features, such as are exhibited by soil fertility and topographic variations, come into prominence again.

Plate 2, fig. 1 presents the appearance of a sandy towhead, as well as sandy accretion areas, on a point bar south of Thomastown, Louisiana. All of these features have been removed from the area of active river action. Eventually vegetation will develop over and preserve these sandy surfaces as it has done already elsewhere in the finer sediments. It can be noted from the photograph that both the towhead and the sandy accretion strip contain distinct sand mounds of fairly uniform size. These have been formed chiefly by eddies and turbulent flows resulting from river action during time of flood and perhaps subsequently modified slightly by wind. It can be noted that the individual magnitude of these sand mounds is the same as is that of typical pimples elsewhere. Likewise, the orientation of these mounds along the pattern of a meander curve is the same as are the arcuate rows of pimples shown in plate 1.

Plate 2, fig. 2, depicts a similar situation in which there has developed a silty sand flat in an abandoned course of the Mississippi River. The locality is near Alligator Lake in Louisiana. It can be noticed that here too there are sand mounds having the individual magnitude of pimples. Many have elliptical shapes and have coalesced. It is observable here that orientations of these mounds are in two directions roughly at right angles. When such dual orientation occurs on limited portions of a fairly extensive sand flat and, if at the same time the mounds are equally spaced geometrically, it is apparent that they may appear to have no particular orientation at all—once they become subdued and incorporated into a more blended topography. This is illustrated in the case of pimples in plate 3.

Plate 3 is an aerial view of the surface at Vincent Island in Louisiana. The island is Prairie Terrace, Pleistocene of age, and therefore independent of the Recent marsh conditions which can be seen to prevail in the northern portion of the view. During the late Pleistocene, this terrace surface carried a silt laden, meandering stream which developed many silty flats such as the channel filling pictured in plate 2, fig. 2. In the south central portion of plate 3 meander scars are still visible, and many coalesced pimples can be seen to have the dual right angle orientations identical to those of the sand dunes of plate 2, fig. 2.

Thus it becomes apparent that meandering behavior of rivers tend to develop silty and sandy concentrations of sediment in individual strips which eventually cover much of the total surface area within a meander belt. As these coarse deposits are forming, their surfaces are sculptured with water-carved mounds. Vegetation quickly moves in to form a protecting cover and, with the formation of a soil profile, these mounds become our familiar pimples.

C. COASTAL PIMPLES

Since the pimples of meander belts have originated from sand mounds on bars, and so forth, it is logical to expect pimples to have been derived also from eolian sand dunes on coastal beaches. The latter is found to be the case.

As a typical example of this sort, plate 4 shows the arrangement of pimples in southern Chambers County, Texas. It can be seen from the inset photograph that this is an area of a former sand spit. Outlines of several stages may be observed from the patterns of ancient beaches at least three of which are yet distinctive. During the times at which these beaches existed, the spit was much longer than at present, its southern part having been since truncated. At the present time, the seaward part of this peninsula contains marshes which present quite a different environment from that which formerly existed. Hence an environment for the formation of dunes is no longer present. But, it can be seen that, during earlier times, there were sandy beaches in this area and upon these beaches, small, eolian sand dunes were formed and preserved. Since these beaches were in a process of migration, their dunes have become spread over a large area but still maintain their orientations parallel to the former shorelines. And with moderate changes occurring over a period of time, these coastal sand dunes have become typical pimples.

The uniformity in size of these former dunes may be related to uniformity of beach areas upon which they have originated. Only within widespread deserts and coastal beaches containing abundant sand deposits are very large dunes able to develop. With restrictions as to area of sand flat and supply of sand, dunes tend to be small in size. An environment of this sort explains the size homogeneity of pimples in this area. Likewise, more abundant sand deposits along beaches in other

areas, which would thus develop few, but very large, dunes, explain the absence of pimple mounds in many sand areas elsewhere.

D. MOUNDS IN GLACIAL DEPOSITS

In certain areas of glacial outwash in western Washington there are the well known "Mima mounds." With regard to size, shape, orientation, and relationship to alluvial deposits, these are essentially similar to the pimples of the Gulf Coastal Plain (cf. Dalquest and Scheffer, 1942).

These mima mounds are formed of coarser materials than are the Gulf Coast's pimples, however their association with glacial outwash channels and their situation on stratified outwash gravels speak for a similar fluvial origin. There is nothing in their physical characteristics to set them apart as unique.

Likewise in other glaciated areas there are features which very closely resemble ancient mound forms. Gwynne (1942, p. 204) has published an airphotograph of an area southeast of Ames, Iowa, which very distinctly contains a pimple pattern although the appearance is much subdued. In this area there are swell and swale features which are interpreted as resulting from oscillations of an ice front of the Mankato lobe of the Wisconsin drift plain.

III. Former Hypotheses of Origin

Suggestions as to the origin of pimple mounds have been put forth by a number of authors. Following are some of the theories together with certain objections as to their universal validity.

1. Legends are the most interesting of the available hypothesis and are quite as logical as are some views expressed by cultured persons. Following are two folk stories reported by Harris and Veatch (1899) regarding pimple mounds of Arkansas, Louisiana, and Texas:

"An old darkey offered the following explanation: when the 'Great Massa' made this earth he made it with a sieve and when he finished the sifting there were a number of lumps left in the sieve. These were thrown out forming the mounds. Another explanation . . (was) . . given by the Caddo Indians. Their legend ran that many, many years ago the country was inhabited by a race of giants. For some reason, which the legend did not state, the giants were

carrying dirt in their aprons; when the dinner horn sounded they dropped the dirt where they stood and hurried away to a dinner from which they never returned."

Objections to these views will be at once apparent to many people.

2. Many brief and generally unsupported views have been presented by writers during the latter half of the nineteenth century. Following are a few of these:

a. According to Marquis de Nadaillac (1895), pimple mounds are of human origin being either garden beds, tepee or wigwam sites, or burial mounds. It is difficult to see how such a dense population as would have been required could ever have lived in these areas and the absence of artifacts or human remains excludes the likelihood of human influences.

b. Hilgard (1873) attributed the mounds to a species of ant which has since disappeared. And Veatch (1905) extended this view to include termites. However, the structures within these mounds show no evidences to this effect and the presence of gravels within and upon pimple mounds of Arkansas and Washington preclude the possibility.

c. A purely wind origin for pimple mounds was recommended by Featherman (1872) and Clendenin (1896). However their hypotheses require an arid climate and in no way do they explain meander patterns, uniformity of mound size, and so forth. Also their views regarding masses of earth lifted by the uprooting of trees in storms and modifications by burrowing animals do not explain greater coarseness of material and the geographic limitations to areas of certain alluvial deposits.

d. Various forms of an "eruption" theory have been suggested by several authors including Hopkins (1870), Clendenin (1896), and Harris and Veatch (1899). These involve springs or aqueous volcanoes resulting from artesian pressures, origins through the action of gas vents, and bulges due to the unequal weight of uneven clay layers on plastic, water-logged sand lenses. Likewise, these modes of development do not explain uniformity of sizes, meander and ancient beach pattern arrangements, etc.

e. Brief statements have been made to the effect that pimple mounds have been produced by a rapid rush of waters and

secondly by a slow differential erosion (Harris and Veatch, 1899). Neither of these views are sustained by facts.

f. Branner and Purdue (cf. Veatch, 1905) have suggested that pimple mounds represent immense concretionary formations and others have advocated unequal weathering of limestone, and even fish nests exposed by elevation. However, these views are too improbable to merit consideration.

3. The mima mounds of Washington have been discussed in an interesting paper by Dalquest and Scheffer (1942). These authors effectively refute earlier theories of origin which have included views that debris was washed into pits on still or moving ice, and that silt, when frozen, cracks into huge polygons which can absorb sediments, and so forth. However their recommendation that these mounds are purely the work of gophers heaping up earth over many generations is equally untenable. Were pimple mounds formed in this manner, it is not likely that they would be limited to areas of alluvial deposits. A shallow lying base of gravels, into which gophers will not burrow, is an integral requirement of the gopher-hypothesis. And the authors suggest that in parts of the country other than Washington a clay hardpan or bedrock may substitute for dense gravel. If this hypothesis is true, then pimple mounds should be common features on thin residual soils overlying bedrock wherever there are gophers. This definitely is not the case. To the writer's knowledge, the most typical pimples are restricted to alluvial deposits and nearly always reflect configurations of these deposits. Gophers cannot account for these essential features.

Also, a strong argument, put forth by Dalquest and Scheffer in favor of gophers, is that "mima mounds" are found on terrace slopes and that other modes of origin cannot account for such occurrences. However, an alluvial origin can be shown to be the case in areas where excessively steep river banks may have the appearance of terraces. This is especially the case when banks are abandoned through river shiftings and become subdued with vegetation. Plate 5 contains an example of distinct sand mounds which were formed by eddying currents during a flood of the Mississippi River and have been left plastered more than midway up a bank over 35 feet in height. It is not improbable that similar features may have formed along swollen glacial streams in western Washington.

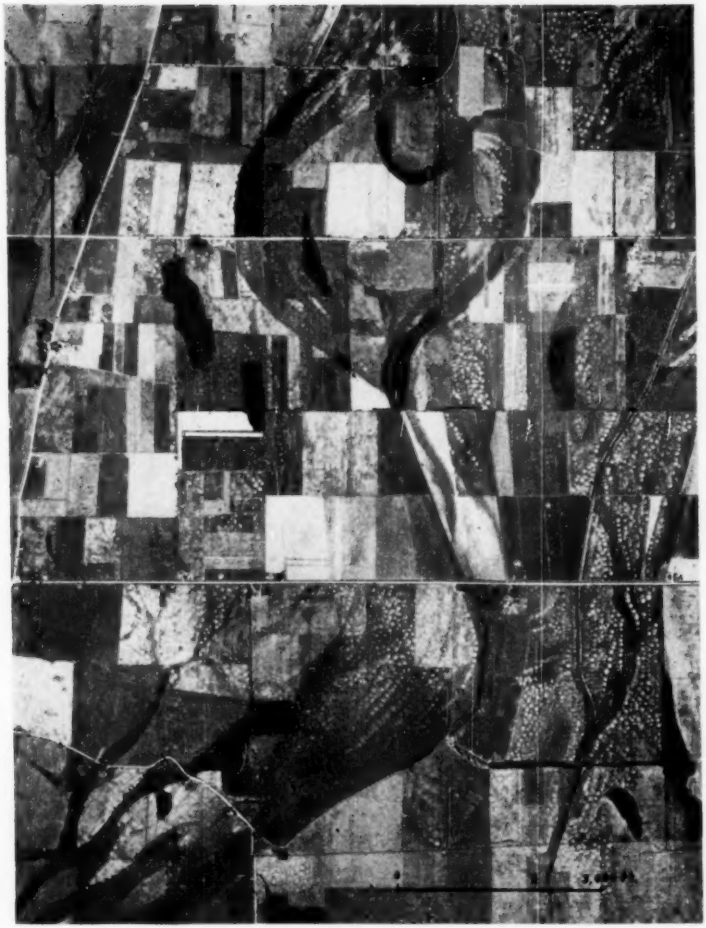

PLATE 1. Pimple mounds at north end of Advance Lowland, near Cape Girardeau, Missouri. Note mound alignments in the pattern of sand accretion ridges on former point bars of a meandering river.

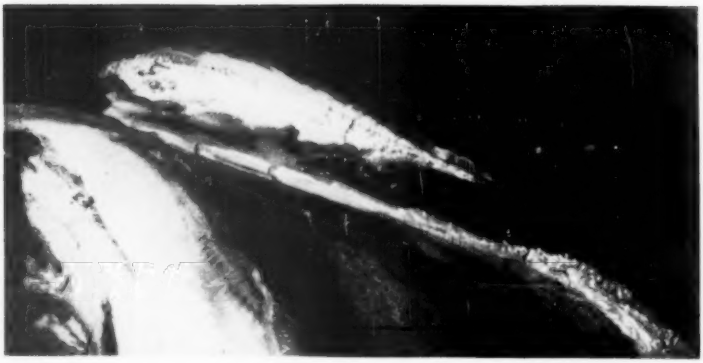

PLATE 2, Fig. 1. Towhead and sand deposits in a partly abandoned river channel. Mounds on the sand deposits have similar shapes and alignments as have pimples. S. of Thomastown, La.

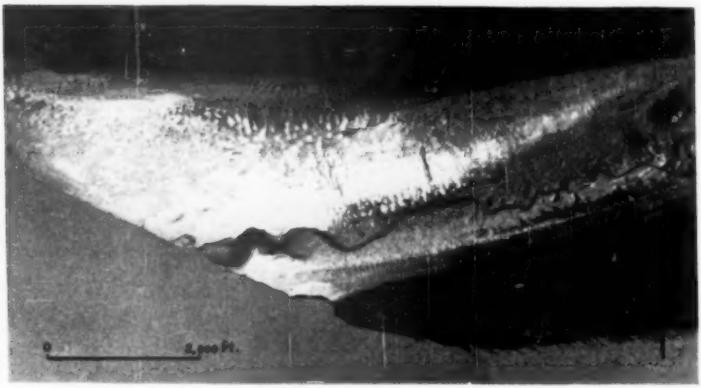

PLATE 2, Fig. 2. Sand mounds formed in an abandoned river channel. Note magnitude and alignment in two directions. 4 mi. east of S. tip of Alligator Lake, La.

PLATE 3. Pimples on the surface of Vincent Island, Louisiana, surrounded by marsh to the north and east. Northward is Black Lake. Pimples pass under the Recent marsh deposits.

PLATE 4. Pimple mounds in southern Chambers County, Texas. Note alignments along old beach ridges and the previous forms of sand spits. AAA photo.

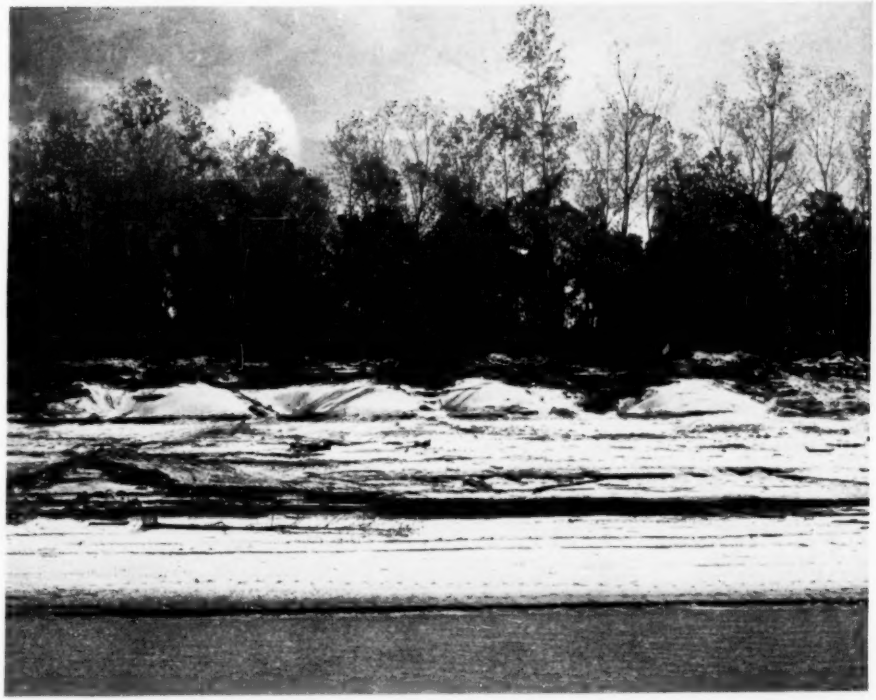

PLATE 5. Sand mounds formed by eddying currents during high water stage. These are plastered along a 35-foot bank slope. East Bank, Mississippi River, Avondale Bend, Jefferson Pb., Louisiana, 1944.

4. A recent theory, which has the merit of being still different from the flood of views already mentioned, is one proposed by Dietz (1945). His suggestion is that the mounds "are water-deposited features originating as sandy islets along the margin of marsh-grass-lined lagoonal swamps. Aerial observation . . . shows these islets along the shore in various stages of formation and grading into mounds preserved on land." This condition is illustrated in plate 3 where it can be seen that pimple mounds extend out into the marsh bordering Black Lake. In the left portion of the view, pimples can be seen to protrude from out of the water. However, this situation does not illustrate growth stages. The pimple mounds in this area are Pleistocene in age and have in part been alluvially drowned by an encroachment of Recent marsh deposits. On the periphery of this encroachment, they protrude from under the Recent covering. Thus, this gradational relationship has been misinterpreted in explaining stages of origin. That Recent deposits have flooded onto Pleistocene surfaces has been proven in bore holes by the presence of oxidized materials directly below the black carbonaceous Recent marsh materials. And, finally, an origin of pimple mounds by development in lagoonal marshlands cannot possibly explain the Missouri pimples in plate 1, or those of western Washington.

The writer does not deny that these processes suggested by earlier workers are adequate for producing pimple mounds. However, their application is restricted and is of the much lesser importance when compared with the much more widespread occurrence of river mound and eolian dune pimples.

IV. Summary

1. Pimple mounds reported from various areas, such as Washington, Missouri, Arkansas, Texas, and Louisiana, are essentially similar.

2. In meander belt areas, pimples conform to patterns of accretion ridges on point bars.

3. Sandy towheads and point bars are observed as containing water and wind developed sand mounds which have identical sizes and orientations as have pimples.

4. It is suggested that such mounds are preserved by mantles of vegetation and later are exposed as the familiar pimple features.

5. In coastal sand-flat areas, dunes are observed to have orientations which indicate the beach origin of typical pimple mounds.

6. Glacial outwash areas, such as in Washington and Iowa, have developed mound forms on their surface which are identical to typical pimples.

7. Pimple mounds, in conformity to the eolian dune and river mound hypotheses of origin, are generally restricted to areas of alluvial deposits.

8. These hypotheses of origin appear to have more universal applications than do other modes of pimple mound origin previously advocated, although the latter theories may remain valid in many special instances.

V. Conclusion

Important modes of origin of pimple mounds are processes responsible for sand dunes along coastal beaches, sand mounds on accretion topography formed by meandering streams, and alluvial mounds deposited from glacial outwash.

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Geology Branch,
U. S. Waterways Experiment Station,
Vicksburg, Mississippi.

CERAMIC PRODUCTS; THEIR GEOLOGICAL INTEREST AND ANALOGIES

W. O. WILLIAMSON

ABSTRACT. Some phenomena of the ceramic industries are analogous to processes believed to operate in igneous, metamorphic, and sedimentary petrogenesis. The shaping of clays and the deformation of rocks produce comparable petrofabrics. The interaction of igneous and country rock is paralleled by that of silicate-melt and refractory. Fronts and culminations exist in slagged refractories, but there is no evidence that they are produced by solid diffusion. Ceramic phenomena that suggest the operation of solid diffusion are, however, recorded.

INTRODUCTION

THE ceramic industry depends largely on the exploitation of rocks and minerals; among its raw materials clay is pre-eminent. The literature devoted to clays is very extensive; those parts of it which are of general interest to geologists are on the whole, relatively accessible and well-known. There exists, however, further literature, scattered through a variety of journals, which is less familiar. Admittedly this literature varies much in scientific value, but in it are described phenomena arising during the manufacture and use of ceramic artefacts that show suggestive analogies, real or apparent, to geological processes. The books by Chesters (1946), Eitel (1941), Norton (1942), and H. Wilson (1927), the various reports on Refractory Materials issued by the Iron and Steel Institute of Great Britain, together with a recent review by Hilliard and McKee (1948) can be recommended to the geologist who wishes to extend his reading into the ceramic field; all these works have extensive bibliographies.

H. Wilson (1927) cites, in a classification, no less than 44 types of ceramic product. Much of the present communication, however, is restricted to consideration of monomineralic ceramic articles, English earthenware, and some important refractory compositions. Further, the interaction of refractories with slags, glasses, and gases is reviewed.

Bowen (1943) has already indicated points of contact between petrology and silicate technology, while Hilliard (1946) noted some analogies between geological phenomena on the one hand, and those encountered in the manufacture and use of refractories on the other.

ARTIFICIAL THERMAL METAMORPHISM

Tomkeieff (1940) has reviewed the nomenclature of the rocks that appear in thermal aureoles and has shown how a classification may be based either on composition or on texture. Benson (1945-46) has found it convenient to adopt that classification which carries a textural significance. Thus "buchite" is used for a vitreous or semi-vitreous material derived from argillaceous or arenaceous sediments, and "porcellanite" for the unvitrified, finely crystalline, metamorphic products of such sediments; "hornfels" is reserved for their less finely crystallised derivatives. The same classification can be conveniently adopted in the present text.

Many "fired" ceramic products, e.g., tableware or chemical porcelain, contain a quantity of glass with which are associated new or relict crysalline phases. They thus find their analogues in the buchites. It is significant that buchites tend to associate, as xenolithic or contact rocks, with minor intrusions, i.e., with intrusions that provided natural "firing" which was relatively short and thus, in duration, showed some measure of approximation to the "firing" of the potter's oven. Thermal treatment has been inadequate to ensure complete recrystallisation. Crystalline ceramic products resembling hornfelses do, however, exist. These frequently contain a single chemical species, with but few accompanying impurities, which has been heated to temperatures below its melting-point; the amount of low-melting material available for the formation of glass has been small. Such artefacts resemble the recrystallised quartzites and marbles; both the factitious and natural products owe their texture more to their monomineralic constitution than to the type of thermal treatment they have received.

The property of recrystallisation at temperatures below the melting-point is utilised in the production of certain ceramic articles, e.g., the well-known alumina ware; the history of this ware has been reviewed recently by Singer and Thurnauer (1947). Stott (1938) has noticed that MgO, BeO, and ThO_2 exhibit the same capacity for recrystallisation.

Recrystallised ceramic products are frequently described as "sintered." Sintering, however, appears to be distinct from recrystallisation, but may be assumed to be the precursor of

the latter process and to merge into it as the temperature is raised. In the operation of sintering, a powder that has been compacted in the cold is heated to a temperature below its melting-point; the mass becomes rigid and coherent. Bangham (1947A; 1947B) has ascribed the coherence to the effect of forces, acting normally to the free surfaces of the particles, of the type which give rise to adsorption, adhesion, and friction. The rigidity of the solid allows these forces to operate initially only over a small area of two contiguous surfaces. This rigidity diminishes, however, as temperature rises; thus the increasing capacity of the solid to deform permits the forces to act over ever widening areas. Presumably the intimate contact finally produced allows the migration of ions from one particle to another and recrystallisation occurs. The natural recrystallisation of rocks would appear to imply an antecedent process of sintering.

Sintered ceramic ware is often shaped by casting and, in consequence, mechanical deformation of the grains does not occur. Buerger and Washken (1947), however, have studied the recrystallisation of strained solids, viz., CaF_2, MgO, $CaSO_4$, Al_2O_3, and BeO. They found that recrystallisation failed to occur below a critical temperature which, for a given material, decreased as the amount of initial deformation increased. The presence of a solvent lowered the temperature at which recrystallisation occurred. Such observations are of interest both to the ceramist and to the student of the dynamic factors involved in metamorphism. However, there seems to be scope for comparing them with the results of other workers who have devoted attention to the physical and chemical changes that can occur in the solid state (Hedvall, 1938A; 1938B). Thus Hedvall reports that the compressive strength of Fe_2O_3 is more markedly augmented by heating over the recrystallisation temperature if this substance has a faulty lattice initially (cf. the strained lattice produced in the compounds investigated by Buerger and Washken).

Of very direct interest to the geologist is the recrystallisation of quartz. This process could be expected to occur during the extended use of silica-bricks in the linings of industrial furnaces, but no record of it has been found in the literature. Dale (1924-25), however, produced a sandstone-like material,

having marked cohesion, by heating ground quartz at ca. 1050°C. under a pressure of 270 lbs./sq. in. This observation suggests sintering.

D'Eustachio and Greenwald (1946) obtained clear evidence of the thermal recrystallisation of quartz under experimental conditions resembling those employed by Buerger and Washken (op. cit.). When quartz-individuals were stressed, they ceased to be crystallographically homogeneous but became polycrystalline associations of units having slightly different orientations. By appropriate thermal treatment the individuality was again restored. Certain structures observable in natural quartz, and presumably to be ascribed to the effects of stress, are significantly like the polycrystalline associations described by D'Eustachio and Greenwald.

CORDIERITE AND MULLITE

"Fired" clays and ceramic "bodies" may contain minerals that are to be found also in buchites and hornfelses. Most clays and bodies, however, are too poor in magnesia to yield cordierite, although this mineral is of frequent occurrence in the rocks cited. Cordierite may be formed, however, if the chemical composition of the ceramic material is adjusted by an appropriate addition, e.g., of talc. Thus Rooksby and Partridge (1940) ascribe the presence of cordierite in glass tank refractories to the use of magnesium compounds by the manufacturers. Shand (1943) found cordierite in a similar situation and believed that magnesium from the glass was involved in its formation. Hausner (1946) has lately reviewed our knowledge of cordierite-rich bodies. Phemister (1938-42) has described interesting occurrences of cordierite in the spent shale of oil-distillation retorts; in some instances this mineral appears to have been formed by simple thermal metamorphism.

A crystalline phase appearing in well-fired clay-containing ceramic articles is a compound that was long thought to be sillimanite. A similar compound had been encountered in buchites, e.g., in those associated with the Tertiary minor intrusions of Mull (Thomas, 1922). Thomas believed that the "sillimanitic" variety of these buchites had resulted from the simple fusion of a sediment having the composition of a highly aluminous fireclay. He directed attention to the comparable but artificial occurrences of "sillimanite" in glass fur-

nace refractories as described, for example, by G. V. Wilson (1918). Bowen, Greig, and Zies (1924), however, were able to show that the "sillimanite" of both Thomas and Wilson was not $Al_2O_3.SiO_2$ but $3Al_2O_3.2SiO_2$; this compound was called mullite. At first there was some tendency to deny that mullite was a real compound, but Taylor (1932-33), among others, insisted that it was not merely an intimate mixture of sillimanite and corundum. Nahmias (1932-33) obtained evidence that there is no series of compounds between sillimanite and mullite, although the X-ray powder photographs of mullite showed some variation; these variations were attributed to the presence of TiO_2 and Fe_2O_3, rather than to differences in the Al_2O_3/SiO_2 ratio. A. J. Bradley and Roussin (1931-32), however, claimed that porcelains contained a material which they termed "porzite"; this, though similar to sillimanite and mullite, was distinct from them. Posnjak and Greig (1933) could not substantiate this hypothesis. The problem of mullite has been investigated more recently by Rooksby and Partridge (1939) who were able to distinguish three varieties of mullite by X-ray powder photography. Heating of alumina and silica in stoichiometric proportions yielded alpha-mullite $3Al_2O_3.2SiO_2$; compounds intermediate in composition between sillimanite and alpha-mullite appeared to be non-existent (cf. Nahmias, op. cit.). Alpha-mullite was not found among the natural mullites examined. When alumina was in excess beta-mullite was synthesised. The presence of iron and/or titanium in solid solution yielded gamma-mullite. Mullites from the classical occurrences in Mull were of the beta and gamma varieties. Most of the ceramic products examined contained mullite which varied in composition between the two extreme varieties, alpha and gamma mullite respectively, according to the amount of iron and titanium present in solid solution.

It is interesting to note that mullite is now prepared on a large scale by fusion-casting in the manufacture of, for instance, glass-tank furnace blocks. Rooksby and Partridge (op. cit.) have found beta-mullite in the cavities and blow-holes of such blocks. Hedvall (1948) has recently mentioned the synthesis of mullite by powder reaction in the presence of metallic oxide catalysts.

The crystallised alumina-silica compound, identifiable in ceramic products by means of the microscope, can be referred

to mullite with considerable confidence. It is less certain that the "sillimanite" of metamorphic rocks, if the mineral has been recognised only on the basis of optical data, is not, in some instances, mullite.

It has now been shown that kyanite, andalusite, and sillimanite can be transformed into mullite by heating; the change occurs most readily in kyanite and least readily in sillimanite (Greig, 1926; Riddle and Peck, 1935). The relative stability of the three $Al_2O_3.SiO_2$ minerals can, indeed, be inferred from the mode of their natural occurrence. In the thermal metamorphism of pelitic rocks andalusite gives place to sillimanite as the metamorphism becomes more pronounced (Harker, 1939). Moreover, Williamson (1935), for instance, has described how the "regional" kyanite of a gneiss is supplanted by andalusite and sillimanite where the gneiss is contact-altered by a later intrusion.

The thermal transformation of the $Al_2O_3.SiO_2$ minerals into mullite has practical significance in the manufacture of refractories based on these materials. The change should have been effected by calcination before the refractory is used; otherwise failure under load may ensue at high temperatures. Failure depends on the change of the alumina-silica compounds to mullite; this change can occur at temperatures below those at which any liquid is formed in the system (Bowen, 1943).

METASTABILITY IN METAMORPHIC ROCKS AND CERAMIC ARTEFACTS

When the metamorphism of a mineral-association is produced by rising temperature and pressure there is a tendency towards the establishment of a new association of crystalline phases; this new association is called into being because the novel conditions demand a corresponding equilibrium assemblage of minerals. True equilibrium may not, however, be attained; thus, for example, andalusite and sillimanite may co-exist in hornfelses. When, on the other hand, temperature and pressure subsequently decline, phases that came into existence at the peak of metamorphism commonly persist; strictly, such phases are now in metastable equilibrium (cf. Harker, 1939).

The type of mineralogical reconstruction that is effected artificially in the ceramic industries can be equated most nearly with the process of thermal metamorphism. The mineral con-

stituents of a ceramic artefact behave like those of a rock in their attempt to attain a new equilibrium in response to a rise in temperature. This attempt is patent, for example, in the relationship that exists between the porosities of fired articles of various compositions and the relevant equilibrium diagrams (Shelton, 1948). Mellor (1907) realised long ago that true equilibrium was often far from being attained—"The reaction between the different constituents of the body, in firing, is arrested before the system is in a state of equilibrium. The chemistry of pottery is therefore largely a chemistry of incomplete reactions . . . ." Mellor interpreted the word "reactions" very liberally in this context and used it to cover not only chemical but a variety of physical changes (Mellor, 1914C).

The presence of glass in a ceramic article is an obvious indication that a metastable condition exists. The persistence of tridymite and cristobalite in ceramic artefacts carries a similar significance; at room temperature quartz is the stable phase.

A PARTICULAR PRODUCTION-SEQUENCE AND ITS GEOLOGICAL ANALOGIES

The manufacture of British earthenware may be represented by the following much abbreviated flow-sheet:—

> Raw materials → mixing "ark" → sieves → magnets → "finished ark" → filter-press → pugmill → making (by shaping the plastic "body" or by casting in plaster moulds) → drying → biscuit-firing → glazing → glost firing.

The raw materials are Cornish china clay, "ball clay" from Tertiary deposits in Devon and Dorset, flint from the Cretaceous chalk (obtained often in the form of beach pebbles), and alkali-granite (Cornish stone). Most of the literature of these materials is enumerated and discussed by Williamson (1938). The china and ball clays can be assumed to be dominantly kaolinitic.

The flint is calcined before it is incorporated in the "body"; this is primarily to make it more friable and thus easier to grind. The calcination causes the flint to show a decrease in refractive index, as determined by immersion, and also in density. Further, the flint, which exhibits aggregate polarisa-

tion initially, may become largely isotropic. The production of cristobalite does not seem to be essential to the initiation of any of these changes. Cristobalite is formed, however, if calcination is adequate, but it shows an anomalously low density. It has been suggested that the fall in the density of flint, which becomes obvious at temperatures as low as 300°C., i.e., prior to the formation of cristobalite, is only apparent. It has been held to depend on the development of minute voids in the structure of the flint which persist even in the cristobalite which is ultimately formed (Simpson and Webb, 1939; Holdridge, Nancarrow and Francis, 1942). The tendency to isotropism could be ascribed to the comminution, during calcination, of the crystalline units in the flint (Williamson, 1941). With this phenomenon may be contrasted the recrystallisation of flint to a quartz-mosaic effected by thermal metamorphism in Antrim (Tilley and Harwood, 1931; Tilley and Alderman, 1934). Harker (1939) cites comparable occurrences in the cherts of various localities. These natural effects may have been determined by the more extended heating, perhaps under "wet" conditions, which the flint or chert received.

Before they are mixed with the clays, the calcined flint and the alkali-granite are ground with water, generally in ball mills. It is possible that the student of natural subaqueous abrasion may find interesting data in the literature of wet grinding of which Creyke and Webb (1941) provide a useful bibliography. These workers have indicated that, in their own experimental grinding of a chalcedonic silica, the rate of comminution increased as the thickness of the hydrated shells around the particles decreased. This thickness is controlled by the nature and the amount of the electrolytes present. Grinding is retarded by the presence of clay. All these observations may have significance in analogous processes of natural abrasion.

The four constituents of the earthenware body are delivered separately to the mixing ark as aqueous suspensions. The suspensions of ball and china clays are discharged into the ark before those of flint and alkali-granite. This is believed to impede preferential settling and consequent segregation. Thus an empirical procedure has been developed which is reminiscent of the experimental results obtained by certain students of the physical chemistry of sedimentation. Boswell (1930) made the

significant observation that an apparently even-grained clay may separate into fractions of markedly different grain-size if it is shaken with water and allowed to settle; further, he was able to show in the laboratory that sand or silt could be trapped in a settling, flocculated, clay and size-grading thus prevented. He used colloidal ferric hydroxide to coagulate the clay; Dreveskracht and Thiel (1941) obtained similar results by employing metallic ions as coagulants. The clays used in mixing an earthenware body approximate to the flocculated state. It would thus appear that the potter, by running the clay suspensions into the mixing ark before the addition of the coarser grained flint and alkali-granite, has, unconsciously, forestalled these experimenters in certain of their results and has, moreover, obtained conditions which in Nature would impede size-grading in a sediment.

The aqueous suspension of "body" is now "de-watered" in the filter-press to obtain a plastic mass. This process involves the formation of a cake against filtering cloths which retain solids while permitting water to pass. The particles in the cake tend to lie with their major surfaces parallel to the surfaces of the filter-cloth (Williamson, 1941). Identical arrangements of tabular particles can be produced by gravitational settling and can be matched by the disposition of the minerals in some igneous bodies, e.g., the gabbro of the Bushveld Complex (Van den Berg, 1946). In the ceramic filter-press, direct mechanical squeezing of the press-cakes does not occur. Pressure is exerted, however, on the solidifying cakes via the liquid column from the pump; thus pumping at an increased pressure produces a filter-cake with a reduced water-content. This squeezing out of water from a mush resembles the mechanical expulsion of residual melt, entrained by crystals, which has been postulated as a factor in the differentiation of magmas. Williamson (in discussion on Van den Berg, 1946) suggested that the linear parallel structures in the Bushveld gabbro might depend on the movements of entrained liquid consequent upon such expulsion, while the banding in the gabbro might be analogous to the segregation-phenomena that are sometimes exhibited by ceramic filter-press cakes.

The earthenware cakes are now fed to a pugmill in which they are cut by knives, compressed, and forced through a die. The resulting extruded column has structures similar to

those found, for example, in the Drachenfels volcanic plug (Williamson, 1941). The particles towards the outside of the column show a planar parallelism that follows the surface. Interiorly, however, there may be structures resembling the flow-lines, produced by tension, which cross the head of a column of magma which was moving forwards before solidification. The analogies between the structures in a column of pugged clay and those in an igneous plug or comparable intrusion could be anticipated from the laboratory studies of Riedel (Williamson, op. cit.), or indeed from the much earlier demonstrations of Daubrée (1879; figs. 141 and 142), in which plastic clay was forced through an orifice. Further experimental work may demonstrate that correspondences exist between the arrangement of joint-systems in igneous rocks and the pattern of drying-cracks that appears in shapes fashioned by the deformation of plastic clay. Certain small fissures in clay-discs have already been shown to be similar in disposition to the fans of tension-cracks which cross the flow-lines in certain igneous intrusions (Williamson 1947). These fissures are not, indeed, drying-cracks but it is to be anticipated that such cracks could develop preferentially at right-angles to directions of tension induced during the fashioning of a ceramic object.

During the biscuit-firing the body attains temperatures of ca. 1150-1200°C. in 60-80 hours; only a few hours are spent at the peak temperature. The effects of firing on the body-constituents may be summarised thus:—

(1) The clay loses chemically-held water; the process becomes marked at ca. 500°C. The solid residue may be regarded as a mixture of finely-divided silica and alumina, although some measure of combination between these oxides has also been considered (cf. Mellor, 1938). As the temperature rises mullite and cristobalite are formed.

(2) The flint changes progressively to cristobalite, although tridymite is the stable phase in the prevailing temperature-range.

(3) The feldspar forms a viscous melt; this melt, during the cooling of the ware, congeals to a glass which serves to bond the new and residual crystalline phases together. Recognisable leucite, produced by the incongruent

melting of potash-feldspar, is unlikely to be encountered because of the brevity of the thermal treatment (cf. Morey and Bowen, 1922).

The mullite and cristobalite in the fired ware are usually insufficiently individualised for discrimination with the polarising microscope; X-ray diffraction patterns and, for cristobalite, thermal expansion data also, may indicate their presence. Quartz, derived largely from the alkali-granite, and flint (cristobalite in part) which is largely isotropic, are very obvious. It is probable that the feldspar-melt tends to dissolve the fine-grained silica made available by the decomposition of the clay, in preference to the coarser quartz or flint (McCaughey, 1937). Bowen (1943) also has indicated a mechanism by which free silica may persist in whiteware to high temperatures.

Mica, from the alkali-granite, may be represented by birefringent pseudomorphs of unknown nature. These, together with the grains of free silica, may, by the arrangement of their major axes, indicate the structural parallelism impressed on the "body" during the plastic deformation that occurred when the articles were shaped; the type of gravitational settling that accompanies the making of ware by casting also produces a specific fabric (Williamson, 1941). The fired ware thus presents a type of "palimpsest" structure.

According to Harker (1939) the presence of solvents is very important for the furtherance of metamorphic changes; these solvents include water. Their actual quantity may be very small. The solvents are believed to induce, in some circumstances, the formation of local glassy patches out of which new minerals crystallise. The solvents, initially held by the glass, are released during the process of crystallisation to perform their work elsewhere. In repetitions of the consecutive processes of glass-formation and crystallisation a small amount of solvent can effect a piecemeal reconstitution of the rock.

In the reconstitution of an earthenware body that occurs during firing the conditions, on the other hand, would appear to be "dry." Further consideration, however, lends less support to this obvious deduction. It is significant that "overfired" bodies "bloat" or develop vesicular structures that can result only from the liberation of gas. According to Austin,

Nunes, and Sullivan (1942) such gas cannot be regarded merely as air that was trapped initially in the pores of the unfired body. Bennett, Dawson, Wooliscroft, and Webb (1941) have investigated the "bloating" of fused granite (Cornish stone) and bodies containing it. They direct attention to the observations of themselves and others that the evolution of water from silicate melts can still occur even at high temperatures. It may be noted that Larsen and Switzer (1939) found 4.57% of water in the glass formed by the natural fusion of a granodiorite by an andesite, although they considered that some of this water had been contributed by the andesite magma. Further, buchites, which earthenware so much resembles, may be appreciably hydrous (Thomas, 1922; Harker, 1939). It may be argued that this hydration entirely post-dates the formation of the buchite. It is noteworthy, however, that buchites may be vesicular (Thomas, 1922) and thus resemble a "bloated"ceramic body. The vesicular character indicates the tendency for a volatile phase to disengage itself from the melted rock. Again, the naturally fused granodiorite described by Knopf (1938) is significantly vesicular and can be directly compared with the artificially bloated granite of Webb and his co-workers (op. cit.). It must, of course, be borne in mind that the solution of volatiles in naturally fused rocks and the vesicularity that arises from their release may depend on the application and subsequent relief of pressure. This may well be true of the buchites described by Thomas (op. cit.), which appear to have been carried up from greater depths. In fused ceramic glasses alterations in pressure are much less likely to be involved.

We are thus left with the impression that, during the thermal reconstitution of some ceramic bodies, volatile solvents may be present, but we cannot assess how far, if at all, they assist in this reconstitution.

The "fired" earthenware body shows a curious property; it expands permanently by a process of hydration. This "moisture-expansion" is among the factors that contribute to the formation of minute tension-faults or "crazes" in the glaze. Comparable "moisture-expansion" has been recorded of a volcanic tuff containing glass and quartz-fragments, which is thus not unlike an earthenware body in constitution (Maloy and Lowe, 1945).

The mechanics of moisture-expansion are little understood. Both chemical and physical mechanisms could be postulated. Among the possible physical mechanisms is an alteration in the balance of the surface and elastic forces that give rigidity to a solid; this alteration would follow the imbibition of water (vide H. W. Webb, in discussion on Bangham, 1947B).

MAGNETITE IN FIRED CERAMIC MATERIALS

Thellier (1933) has noticed that fired ceramic articles, which have cooled in a magnetic field, exhibit a weak permanent magnetism. The observation was not novel, for Mellor (1914B) had shown that materials as diverse as bone china and common brick contained crystals of magnetite to which the magnetism could be related. Fe_3O_4 is usually the stable oxide of iron at the peak temperatures of the ovens and kilns of the clay industries. Harker (1939) cites comparable instances of the production of magnetite by thermal metamorphism; among them is the development of this mineral from the Harz hematites in the aureole of the Brocken granite.

CERAMIC GLAZES AND NATURAL GLASSES

The chemical compositions of most ceramic glazes depart widely from those of rocks. Structural analogies may be expected, however, between glazes and volcanic glasses; indeed, bubbles, flow-lines, and spherulitic and other crystal-arrangements resulting from devitrification, are common to both.

The composition and cooling-rate of most glazes are so adjusted that devitrification is prevented and a bright glaze results. In "crystalline" glazes, however, devitrification is deliberately promoted; Norton (1937) has made a careful study of the conditions necessary for the controlled production of these glazes. A well-known type of glaze contains zinc in amounts sufficient to yield megascopic crystals of a compound that Mellor (1914A), on the basis of a quantitative chemical analysis, has identified as willemite. Norton (op. cit.) appears to be unsatisfied by this identification. The compound has the interesting property of taking up cobalt from the surrounding glaze. The crystals then become blue and the glaze in this vicinity is correspondingly paler (Mellor, 1937, provided a good colour photograph). Singer (1946) suggested

that the similarity in the ionic radii of Co^{++} and Zn^{++} was the basis of this phenomenon; further, he stated that if cobalt and manganese co-exist in a glaze, the zinc silicate crystals abstract the cobalt preferentially. Thus the cobalt colours the crystals and the manganese the groundmass of the glaze. The impoverishment of a glaze in cobalt in the vicinity of zinc-containing crystals appears to be a specific example of the development of the "crystallisation haloes" that are not infrequent in partially crystallised glasses. Thus such haloes are reported and figured around hercynite in the glassy products of the reaction between the contents of a glass-furnace and its refractory lining (Seal, 1948) and around magnetite of similar occurrence (G. V. Wilson, 1918). Comparable examples of the "clearing" of glass around crystals contained therein are to be found in the pitchstones of Arran (Tyrrell, 1928) and in the glass of a naturally fused granodiorite described by Larsen and Switzer (1939).

THE PETROGRAPHY OF SOME TYPICAL REFRACTORIES

Firebricks

The commonest type of firebrick is made from a clay that contains free quartz. A well-burnt brick is likely to show mullite and cristobalite, derived from the clay-minerals, with some residual quartz. The crystalline phases are cemented by a glassy bond. More intensive thermal treatment of the brick causes enhanced solution of the free silica in the fused glass (e.g., see Jay, 1939).

Silica Bricks

A typical silica brick contains, when still unburnt, quartzite fragments in a matrix of slaked lime and quartz-flour. If the temperature and duration of burning are adequate, the quartzite fragments change wholly, or more usually partly, to cristobalite. This change begins at the exteriors of the fragments and along the intergranular or other cracks that penetrate them. The matrix of the fragments is, on the other hand, a meshwork of tridymite units in a lime-rich glass that may contain some crystals of a pyroxene, such as wollastonite. Quenching experiments by Scott (1925-26; 1930) suggest that this tridymite meshwork is in existence at high temperatures and does not make its first appearance only during the

actual cooling of the brick. The lime-rich matrix thus serves as a mineralising agent. Tridymite may be found also as fringes to the cristobalite-quartz assemblage which represents the original quartzite fragments (Thomas, Hallimond, and Radley, 1920; Rigby, White, Booth and Green, 1946).

It has long been realised (e.g., by Thomas, 1922) that silica bricks and siliceous xenoliths resemble each other in both mineralogical constitution and structure. Thus the thermal metamorphism of a feldspathic sandstone may yield a rock containing quartz fragments in a glassy matrix from which tridymite has crystallised (e.g., see Harker, 1939, fig. 21A). However, cristobalite is not reported in association with the quartz fragments. The tridymite is commonly replaced by pseudomorphous quartz; in silica bricks, on the contrary, the tridymite is preserved. The rapid cooling of silica bricks after burning may be responsible for this difference. Further, we do not know if the tridymite would change to quartz when bricks were stored for periods of time geological in duration.

Lacroix (1946) also has described siliceous xenoliths and compared their structures with those of silica bricks. However, he made the fantastic assumption that the appearance of glass around the quartz of the xenoliths indicated that temperatures of at least 1750°C. had been attained. It is clear from the investigations of Holmes (1936) and of Holmes and Harwood (1936) that such glass cannot be assumed to be fused silica; indeed, some glass described by these authors had the composition of potash-rich acid obsidian. Lacroix offers no chemical data in support of his thesis; the fact that the glass he described contained crystals of pyroxene suffices to indicate that it is unlikely to be merely fused silica.

Magnesite Bricks

Although these bricks are named after the raw material from which they are manufactured, they really contain periclase derived from it by calcination. This periclase may be accompanied by minor amounts of other phases of which the nature is determined largely by the types and amounts of impurities in the initial magnesite (cf. Rigby, Richardson and Ball, 1947).

In one manufacturing process, periclase, produced from magnesite by calcination, is allowed to undergo partial re-

hydration; brucite is formed (Chesters and Weyl, 1932-33). Thus the synthesis of brucite follows the mechanism that has been postulated for the formation of the mineral in thermally metamorphosed magnesian limestones. This classical explanation of the formation of brucite in such limestone has, however, been rejected by Keith (1946) for certain specific occurrences in Ontario; he prefers an hypothesis of the direct replacement of dolomite through the agency of magnesia-bearing gases or solutions. Tilley (1947) has, however, recently mentioned an occurrence where the classical theory can be invoked.

Calcined Dolomite

It has been shown experimentally that the initial change during the calcination of dolomite involves the formation of periclase and calcium carbonate (Bradley and Jay, 1946); with this result may be compared the observed occurrence of periclase and calcite in thermally altered dolomites or dolomitic limestones. A difficulty encountered in the use of dolomite refractories that contain some silica is the tendency to "dusting" which depends on the change from beta to gamma $2CaO.SiO_2$. The same phenomenon is seen in contact metamorphic assemblages containing $2CaO.SiO_2$; it may be obvious in the field (Tilley, 1947) or become apparent when material is ground during the preparation of thin sections (Tilley, 1929).

Chromite Bricks

These are made by "burning" chromite with its associated gangue minerals such as serpentine. The matrix of the brick develops from the gangue and additions are sometimes made to increase the refractoriness of this matrix. The writer is unaware of any record of the natural thermal metamorphism of a chromite deposit that would permit a comparison to be drawn. The study of chromite by the ceramist has, however, yielded results that may interest the mineralogist. This study has involved the investigation of natural chromite, the synthesis of a number of spinels, and the investigation of the effects of heating and of various atmospheres upon natural and artificial spinels (see especially Green et alia, 1946).

Chrome-Magnesite Bricks

The prominent constituents of the burnt bricks are periclase, forsterite, and chromite.

CARBON DEPOSITS IN FIREBRICKS: THEIR ANALOGY WITH NATURAL GRAPHITE

Fragments of iron-rich minerals may exist in fireclay and, in bricks made from it, become loci of carbon deposition. This deposition occurs if the bricks are used in an atmosphere, for example that of the blast furnace, containing gaseous compounds of carbon. The loci are associated with grains of magnetite or other ferruginous material which promote the formation of graphite from carbon monoxide or gaseous hydrocarbons. The brick is actually disintegrated by the formation of graphite in its pores.

The occurrence of this type of reaction should be of interest to those who have suggested that volatile compounds of carbon are involved in the formation of deposits of natural graphite. Davidson (1942-44), for instance, could accept carbon disulphide or oxysulphide, or carbon monoxide or dioxide, as the source of the graphite in certain crystalline limestones of the Outer Hebrides. Here dedolomitisation could have made carbon dioxide available. Similarly Wadia (1943) suggested that carbon monoxide or dioxide were involved in the formation of the graphite deposits of Ceylon. Dissolution of limestone in charnockite magma could provide the carbon compounds.

THE ATTACK OF MOLTEN SILICATES ON REFRACTORIES

Most refractories are not homogeneous; they consist of grains of high melting or softening point with, in the intergranular spaces, more fusible material which, in some instances, is the glass that developed when the refractory article was burnt during manufacture. Attack by a silicate melt is thus likely to be preferential. Pores are invaded and glass or other readily fusible constituents assimilated by the melt; particles of high melting point or the refractory reaction-products of these, tend to pass into the aggressive liquid as slowly dissolving xenoliths or xenocrysts. Thus Partridge and Seal (1944) discussed the implications of the well-known observation that molten glass enters glass furnace tank blocks

via the intergranular glassy layers and releases "stones" which float away in the fused batch. These "stones" or xenoliths may consist of grog (pre-calcined clay), sillimanite, mullite, etc., or their reaction-products such as corundum. Comparable phenomena are demonstrable at igneous contacts; Williamson (1935), for instance, described the attack of a granodiorite magma on a gneiss which had been thermally altered to alternating quartz-feldspar and aluminous hornfels layers. The less refractory quartz-feldspar layers were penetrated in preference to those of hornfels.

The attack of fused silicates on refractories is likely to be enhanced if compounds capable of providing low-melting eutectics can be formed with some of the material attacked, although the rate of reaction and the "wettability" of the refractory have also to be considered (Norton, 1942, pp. 494-521). Thus the volume of the attacking melt is augmented and the phases most resistant to solution are launched therein. Brammall and Harwood (1932) deduced just such a mechanism for the interaction of the Dartmoor granite and the shales of its aureole. Silica and alkalies from the magma promoted the formation of quartz and feldspar in the shale; the selective fusion of these minerals allowed andalusite and other refractory compounds that had developed in the shale to pass into the melt as solid phases. In this instance only some constituents of the magma entered the shale. Similarly certain constituents of an invasive silicate melt may effect preferential entry into a refractory with which the melt is in contact; Seal (1948) cites an example where Na_2O and B_2O_3 from molten glass behaved in this way.

The attack of silicate-melts on refractories or of igneous rocks on their confining walls, if it follows the schemes just outlined, bears a resemblance to the marine erosion of a series of alternating hard and soft sediments. However, the attack may achieve more complicated results by the production of selvedges, skarn-like deposits, and zonary structures. Thus a selvedge accompanies the Dartmoor granite contact just discussed. Artificial selvedges and cognate structures are described later.

Preston and Turnbull (1941) have discussed the mechanism of a peculiar form of attack by molten glass on refractories known as "upward drilling." This attack is characterised by

the appearance of pits on the downwardly facing surface of the material affected. These pits mark the sites of bubbles in the glass and the enhanced corrosion of which they are witnesses depended on periodic changes in the surface energy of the melt bounding the bubbles. Comparable natural phenomena do not appear to have been recognised, but Preston and Turnbull have suggested that geologists should consider if volcanic pipes could originate by "upward drilling."

CONTACT AND RELATED PHENOMENA IN GLASS FURNACES

The Classical Investigation by G. V. Wilson

G. V. Wilson (1918) made a notable contribution to the study of those phenomena of interest to the geologist that may be encountered on glass works. He had, for instance, access to a burst tank furnace from which the molten glass had poured into the arched space beneath. Here the glass, by entering into various relationships with the bricks and mortar, had simulated the structures of an igneous complex. These structures varied from injection breccia, through simple and composite veins, to stringers containing both glassy and crystalline material where the glass was disposed either marginally or centrally. Various artificial minerals were also to be found; of these perhaps the most unusual were euhedral quartz and a species identified as biotite. The premature chilling of the glass had left for study xenoliths of limestone that, in circumstances more propitious to the glass-maker but less fortunate for the mineralogist, would have dissolved completely in the fused batch. These xenoliths had paragenetic mineral-associations resembling those of the chalk-dolerite contacts of Scawt Hill, Co. Antrim, Ireland. Associated with the xenoliths were augite, wollastonite, melilite, and the compound $3CaO.2SiO_2$. The mineral form of the latter has recently been identified by Tilley (1942) at Scawt Hill and named "rankinite." The same authority had already shown that $2CaO.SiO_2$ occurred naturally in the same locality. This mineral he christened "larnite" (Tilley, 1929). He has recently demonstrated, with Vincent, that, in addition to β-$2CaO.SiO_2$ or larnite, a rarer mineral, which is α'-$2CaO.SiO_2$, is to be found; for this the name "bredigite" was proposed (Tilley and Vincent, 1948). Further, Tilley (1942) has identified larnite in Wilson's artificial material. In both the natural and artificial

assemblages rankinite separates wollastonite from larnite thus—

Locality	*Source of Lime*	*Artificial Compound or Natural Mineral*			*Source of Silica*
Glass Furnace	Limestone Xenolith	$2CaO.SiO_2$	$3CaO.2SiO_2$	$CaO.SiO_2$	Molten glass
Scawt Hill	Chalk	Larnite	Rankinite	Wollastonite	Flint nodule

It is interesting to note the similarity of this scheme to that used by Jander and Hoffman (1934) to illustrate the results of their studies of the reaction between CaO and SiO_2 in the solid state at temperatures from 1000°C. to 1200°C. Their schematic figure No. 8(3) shows the same calcium silicates as are indicated in the above scheme in precisely the same order between solid lime on the one side and solid silica on the other. They believe that CaO diffuses more rapidly than SiO_2 and determines the arrangement of the calcium silicates between the two solid reactants. Bowen (1940) has suggested the phases that may be expected to come into existence in a siliceous limestone as temperature rises; these phases have a definite and progressive sequence. In this sequence wollastonite appears earlier than larnite, and Bowen suggested that rankinite, the supposed absence of which at Scawt Hill he comments upon, has a minimum temperature of existence above the maximum temperature prevalent during thermal metamorphism. The arrangement of the calcium silicates at Scawt Hill and in Wilson's material, together with the experimental studies of Jander and Hoffmann (op. cit.), indicate that diffusion rather than thermal stability may determine the nature of the calcium silicate produced. Indeed, Jander and Hoffmann state that $2CaO.SiO_2$ is in general the primary product of the lime-silica solid reaction. No doubt, however, there may be time-temperature conditions where, as assumed by Bowen, thermal stability is of major importance in deciding which calcium silicate shall appear, or more probably, survive.

The Formation of Alkali Minerals

The presence of abundant alkalis in many glass batches allows the synthesis of alkali-minerals. Thus Lambeth (1946) has described the formation of nepheline and aegirine in the

fireclay recuperator tubes of a glass furnace. The minerals originated from soda out of the glass batch and Fe, Al, and Si contributed as fly ash by the gasified coal in the producer. The fireclay refractories were therefore not involved. McCaughey (1937), however, has illustrated a reaction, in a similar environment, in which highly aluminous checker bricks have, with sodium sulphide, yielded lapis lazuli; the sodium sulphide is made available by the reduction of sodium sulphate in the glass batch.

Most glass tank furnace blocks contain appreciable mullite; during the use of such blocks the mullite may become involved in reactions that produce corundum and alkali-minerals. For example, Insley (1945) has mentioned that, above the glass-line, alkali-vapours and dust may convert the blocks to a meshwork of corundum crystals, from the interstices of which a molten alkali-containing silicate may drain. Seal (1948) has commented on the fact that the presence of foreign materials allows the meritectic reaction that produces corundum from mullite to occur at lower temperatures. Corundum so derived may enter the molten glass to give "stones," while the invasive foreign materials unite with the residue of the mullite molecule to provide a liquid which drains from the tank block and is capable of crystallising as oligoclase, labradorite or, more rarely, nepheline (Insley, 1945). The course of the reaction below the glass-line, i.e., where molten glass itself is available, is in general similar. Insley notes an increase in the amount of glass in the refractory, the development of corundum, and the formation of a melt which, in appropriate circumstances, may crystallise as nepheline and carnegieite. Even a refractory containing appreciable free quartz can yield corundum in this way. The chemical mechanism producing corundum is reminiscent of the desilication-process which Du Toit believed to be responsible for certain natural occurrences of this mineral (vide Du Toit in discussion on Brandt, 1946). Insley, however, directs attention to analogies between the artificial mineral-assemblages containing corundum and certain natural assemblages that differ somewhat from the desilicated pegmatites studied by Du Toit. These natural assemblages are the associations of corundum with syenite or nepheline syenite at contacts with alumina-containing country-rocks. Such contacts can be likened to those between molten glass and alum-

inous refractories. Because tank-block compositions containing appreciable free quartz are still able to yield crystallised alumina, Insley surmises that the country-rock associated with a syenitic intrusion need not be abnormally aluminous in order to produce corundum.

THE SYNTHESIS OF ALKALI-MINERALS IN THE BLAST FURNACE

Alkali-vapours from the burden are known to cause the formation of alkali-minerals in the firebrick of the blast-furnace. Rigby and Richardson (1947) have shown that kalsilite and leucite are so produced, apparently by a type of artificial pneumatolysis or metasomatism. Such occurrences recall the demonstration by Holmes (1945) of the leucitization of certain rocks by potash-rich lavas; the rocks so affected were granite and, to quote a rock nearer in chemical composition to the firebrick of blast furnace linings, phyllite.

SKARN FORMATION AND COGNATE PHENOMENA

The contact between igneous and country rock is sometimes accompanied by a zone in which one or more mineral species are concentrated. These species may or may not occur also in the invaded country rock. Thus Williamson (1935; fig. 8) depicts zones of hornblende or pyroxene at the contacts between igneous veins and hornblendic or pyroxenic hornsfels respectively. Nockolds (1934) instances remarkably similar zones and applies to them the term "skarns." The examples of skarns just cited are very small-scale phenomena; the choice of examples has been made to facilitate comparison with ceramic occurrences of not very dissimilar magnitude. Thus a type of skarn appears at the interface between a glaze and a pottery body if the glost temperature has been sufficiently high. Mellor (1907) long ago provided a photomicrograph of such an occurrence in a crucible of Berlin porcelain; acicular crystals project into the glaze from the surface of the body. Similar occurrences are common and, where such fringes of acicular crystals exist, the surface of the associated body has usually been markedly corroded by the molten glaze. The crystals are commonly identified as mullite. This compound, which may exist in the body itself, may be considered to have grown under the mineralizing influence of the glaze. The solution of body-constituents in

the glaze, followed by the crystallisation of these materials as the glaze cooled, also can be regarded as having increased, or even initiated, the growth of the mullite fringe. Some skarns at natural contacts could owe their formation to the regrowth of minerals pre-existent in the country-rock; other skarns contain mineral-species not to be found therein. Artificial skarns show the same phenomena. While some consist of mullite, which is seen also in the body, others contain compounds which the body does not. Such compounds were noticed, for instance, at the glaze-body interface, by Parmelee and Buckles (1942); anorthite was among them. Indeed, anorthite and other plagioclase feldspars are common reaction-products also at contacts between glasses or slags and refractory materials. G. V. Wilson (1918) described oligoclase which appeared at the junction between glass and a brick. Towards the brick the oligoclase was rich in "sillimanite"; this observation was held to indicate that the brick had been supplying alumina for the synthesis of the feldspar. The feldspathic reaction-rims surrounding some of the xenoliths in the tholeiites of Mull show a similar concentration of "sillimanite" towards the buchites which they border (Thomas, 1922). Phemister (1938-42) noticed a bytownite skarn between a slag and a firebrick. Hugill and Green (1939) provide remarkable serial photomicrographs in which the genesis of anorthite-skarn, by reaction between blast furnace slag and firebrick, can be traced.

Some type of diffusion must be involved in the production of these feldspathic artificial skarns. Biotitic selvedges, which are among their natural analogues, have been ascribed by Reynolds (1947) to the operation of diffusion. Solid diffusion, however, is specifically implied; this type of diffusion cannot be the main mechanism involved in the formation of artificial skarns, for here molten material is available. The problem of solid diffusion in ceramic materials receives further attention later.

ZONARY STRUCTURES IN SLAGGED REFRACTORIES

Special interest is attached to these structures because, if it is permissible to borrow the terms from petrology, they provide evidence of "fronts" and "culminations" as defined by Reynolds (1946).

The classical example of a zonary structure appears in used silica bricks from the roof of the basic open hearth steel furnace. Over 20 years ago Scott (1925-26) gave a careful description of the phenomenon. The considerable literature that has now accumulated was recently critically appraised by Dodd and Green (1939). The invasive ferruginous material from the furnace constitutes an iron "front"; as this front is established the lime-silica matrix of the brick retreats and thus gives rise to a lime "front" a few inches behind the hot face of the brick. The existence of the lime "front" is witnessed, in the cold brick, by the presence of a zone rich in yellowish glass. In this zone lime, and also alumina, achieve a "culmination." Scott (op. cit.), Greig (1927), and later Dodd and Green (op. cit.) have indicated that the location of this culmination is determined by a correlation between the fusion temperatures of the relevant mixtures and the temperature gradient in the brick. The effect of the temperature gradient on the disposition of the zones, relative to the hot face, is readily demonstrated from the data that Harvey (1935) has presented, partly in the form of colour photographs; the disposition of the zones is seen to have been altered by backing the brick with heat-insulating material and thus modifying the temperature-distribution within it.

The invasion of chrome-magnesite bricks by ferruginous material produces a zonary structure which is well described by Hugill and Green (1938, 1939); this structure appears to arise by a mechanism somewhat different from that which operates in silica bricks. The hot face of the attacked brick develops a blue-black, loosely granular, and apparently unfused layer, but behind this is a brown layer showing signs of fusion. It is generally agreed that the incoming iron causes a swelling of the chromite grains and thus their magnesian matrix is compelled to migrate away from the hot face. The solidification of this migratory material produces the brown layer showing signs of fusion; in this layer there is a "culmination" of magnesium. Zerfoss and Davis (1946) have suggested a mechanism by which the migration of magnesium could be assisted; forsterite, which forms the matrix of the chromite at the hot end of the brick, is assumed to take up iron and thus to become more fusible. The iron-enriched olivine travels towards the interior of the brick where iron is

abstracted from it by periclase and chromite; its solidification as a more magnesian, i.e., more refractory, olivine is thus assisted.

Zerfoss and Davis (op. cit.) consider that the swelling of the chromite-grains, by virtue of which the matrix of the brick is constrained to move, depends on the deposition of magnetite on chromite-nuclei; indeed, the grains of chromite become demonstrably euhedral as their re-growth proceeds (Hensler and Zerfoss, 1947). Zerfoss and Davis (op. cit.) admit, however, that actual solid solutions between chromite and magnetite may form. This admission accords with the change in lattice spacing, noted by Lynam, Chesters, Howie and Jay (1942), which occurs when chromite absorbs magnetite. The work of Lovell, Rigby and Green (1946) has, however, indicated the complexities of the problem of the "swelling" of chromite-grains; they suggest that "bursting expansion" occurs if an actual structural re-arrangement of the spinel lattice accompanies solid solution.

Adams (1930) has described certain artificially produced zonary structures; his description has since been quoted on several occasions in petrological literature. An edge of a dolomitic magnesite brick, containing magnetite, was in contact, at temperatures up to ca. 1430°C., with the face of a low lime magnesite brick. Although the latter brick retained its shape, it showed, in the vicinity of the line of contact, an enrichment in iron and magnesia; the iron was certainly invasive. The incoming material caused a lime-alumina-silica front to develop ahead of it, reminiscent of that found in silica bricks from the roof of the basic steel furnace. Thus lime, for instance, rises to a "culmination" and then falls sharply. Read (1934) remarked on the similarity between the phenomenon described by Adams and certain zonal associations of minerals that appeared around isolated fragments of ultra-basic rock when the country rock was permeated by acid materials. The oxides in these zones showed typical "culminations." Phillips and Hess (1936) described comparable zonal associations of minerals and, independently, postulated processes of migration to account for them which were similar to those which Read assumed to have occurred; however, they dissented from Read's opinion that the various zones had been formed contemporaneously.

THE PROBLEM OF DIFFUSION AND REACTION IN THE SOLID STATE

The hypothesis that diffusion and reaction in the solid state, without the intervention of a liquid or gaseous phase, are involved in petrogenesis has lately been resurrected from obscurity. Only a few years ago it was regarded with open disfavour. Thus Harker (1939) stressed the importance of solvents in promoting reaction and repeated the dogmatic statement, already made in the first edition of his book (1932) that "no sensible reaction can in general be verified at the contact of two crystalline bodies." This may well be true of those instances where, as he points out, a thin section of a metamorphic rock may show several bands of contrasting chemical composition in a single field of the microscope. The statement, however, receives no support from the experimental results of Hedvall and many other investigators (Hedvall, 1938A, 1938B, 1948). Nevertheless, it can be granted that reactions occurring by virtue of solid diffusion may be accelerated by the presence of water-vapour, e.g., the reaction between calcium oxide and silica studied by Jander and Hoffmann (1934) behaves in this way. Read (1933), writing at about the same time as Harker, criticised Stillwell for laying too much stress on solid diffusion as a factor in the genesis of metamorphic rocks; he believed that many petrologists would join him in this criticism. In 1939 he still regarded solvents, including water, as necessary to the changes accompanying regional metamorphism (Read, 1939). Some recent publications incline to a different view. Thus Holser (1947) clearly recognised that diffusion of ions, in the absence of a fluid, may be of great importance in metasomatic processes, while Bugge (1946) laid great stress upon solid diffusion as a promoter of metamorphic changes, particularly at depths where intergranular penetration by fluids may be expected to be difficult. Holmes and Reynolds (1947), discussing metasomatic metamorphism in Donegal, cited evidence which suggests that migration of ions along crystal boundaries and through crystal lattices, rather than the intervention of liquid and gaseous phases, have produced the phenomena which they describe. Barth (1947) is prepared even to accept the formation of some rocks by petroblastesis, i.e., by the direct crystallisation of diffusible ions; if the ions do not crystallise per se, but react with a pre-existing rock, the process is still classed by Barth

as one of metasomation (cf. Holmes and Reynolds, op. cit.). Backlund (1946) points out that the somewhat elusive emanations that are thought by certain petrologists to be potent factors in petrogenesis should be regarded as migrating ions rather than as liquid or gaseous media for ionic transport. However, the two conceptions of emanations are not necessarily sharply distinguishable, for the ions at crystal interfaces are in an exceptional condition and capable of travelling virtually as a fluid film.

It is thus worthwhile to review ceramic phenomena to see if they provide evidence of solid diffusion and reaction which, by virtue of analogies with inferred petrogenetic mechanisms, may be of interest to the geologist. Reynolds (1942), for instance, directed attention to the zoned magnesite brick described by Adams (1930) and discussed earlier in the present study. Reynolds stated—"if it be objected that migration of elements or oxides is an unknown physical process, reference need only be made to the solid diffusion in bricks described by Adams (1930)." Backlund (1946) appeared to interpret the results of Adams in a similar way. Actually there is no evidence that solid diffusion was the principal mechanism involved in the production of the phenomena noted by Adams, although such diffusion may have operated within individual crystals; the lack of microscopical data impedes interpretation. It is probable that an intergranular liquid, determined by the presence of components that could yield low-melting eutectics, was the principal cause of the zonary arrangement. This possibility is explicitly recognised by Adams (op. cit.) and is rendered very plausible by the existence of a region of actual vitrification in the zoned brick near the line of contact with its neighbour. Greig (1927) and Dodd and Green (1939) postulate that a migrating liquid is responsible for the comparable zonary structures in silica bricks. These authors indicate that the concentration of compounds in specific zones follows from the fusion points in the relevant systems and the temperature gradient through the brick (cf. Scott, 1925-26). The fact that a zoned brick, such as the example described by Adams, retains sufficient cohesion at high temperatures to keep its shape, is no argument against the existence of fluid constituents therein. For instance, ordinary white earthenware contains considerable glass, which represents a silicate-

melt that once existed in the heated articles, yet it does not become distorted if the "firing" operation proceeds normally.

It has been mentioned already that Read (1934) draws comparisons between certain zoned structures produced by metamorphic differentiation and the phenomena discussed by Adams; he joins Phillips and Hess (1936) in believing that these structures were produced under "wet" conditions. Reynolds (op. cit.) cites the same phenomena to illustrate solid diffusion, i.e., diffusion under "dry" conditions.

Thus the zoned ceramic structures discussed above would appear to depend for their formation more on the existence of an intergranular or pore "magma" than on solid diffusion. However, some ceramic phenomena permit the operation of solid diffusion to be inferred with reasonable certainty. This is true, for instance, of the interaction between aggressive ferruginous material and the chromite of chrome-magnesite bricks (vide supra). The descriptions and photomicrographs of Hugill and Green (1938; 1939) show that the grains of chromite are not merely enlarged by the deposition of magnetite upon them; the original colour of the grains is progressively obliterated by the extension of an invasive darker periphery. Finally even the centres of the grains are affected. Hedvall's account of the diffusion of iron into quartz illustrates a comparable occurrence and one which is on the same small scale (Hedvall, 1938A, 1938B).

The zonary structures found in certain ceramic objects may require, for their formation, migrations a few inches in extent, but even these migrations are not governed by the process of solid diffusion; where the existence of solid diffusion can be substantiated it has a scope which does not go beyond that which is involved, for example, in the exsolutional phenomena shown by feldspars. Some hypothetical petrogenetic mechanisms may require migrating ions to travel for miles by a process of solid diffusion. Geological time is, relatively, enormously long; thus, once we have experimental evidence of solid diffusion, we may argue from the minute to the grandiose, as Backlund (1946) suggests that we perforce must do. However, if we cite artificially induced phenomena to support an argument by analogy, we must first be sure that the analogy is sound.

SUMMARY

Recrystallised "monomineralic" artefacts show analogies to thermally produced quartzites and marbles. Fired complex ceramic bodies resemble buchites; both contain glass and new or residual crystalline phases. Mullite may be one of the new phases. Natural and artificial occurrences of mullite are discussed in the light of recent experimental work. While the alumina-silica compound found in ceramic articles may be referred to mullite with some assurance, there is less certainty as to how much natural "sillimanite" is really mullite. The conversion of kyanite, andalusite, and sillimanite into mullite is important in the manufacture of alumina-silica refractories; the ease of conversion of these minerals, determined experimentally, accords with their behaviour during contact metamorphism.

Both thermally metamorphosed rocks and fired ceramic articles may show a progression towards high temperature equilibria which are not ultimately attained; the phase assemblage that persists after cooling is metastable but indicates how far this progression has gone. It is not certain that the mineralogical changes that accompany the firing of ceramics have always occurred under strictly "dry" conditions. The high temperature "bloating" of some ceramic bodies is significant and recalls the vesicularity of buchites.

The mineralogy of typical refractories is described. Silica bricks resemble siliceous xenoliths. Experimental studies of basic refractories have shown that the formation of periclase from magnesite and, in association with calcite, from dolomite, and the subsequent change of periclase to brucite by hydration, occur in a manner comparable with that suggested by the evidence from igneous contacts.

There are analogies between the action of glasses and slags on refractories and that of igneous intrusions on country rocks. In both instances the melt may be augmented by low-melting constituents, while the more refractory compounds, that are residual or produced by reaction, are launched into the melt as xenoliths.

Reactions between glass and refractories may lead to the synthesis of alkali-minerals. Desilication may produce corun-

dum. Blast-furnaces provide a second locus for factitious alkali-minerals.

The formation of skarns and zonary structures at the contacts between silicate-melts and ceramics is described. Fronts and culminations exist, but it is not certain how far they are comparable in origin with their natural analogues. Migration of a melt rather than solid diffusion appears to be involved in their production. When evidence of solid diffusion is available it indicates a very small-scale effect. Because of the importance of the time factor such evidence cannot lead to outright denial of more formidable effects under natural conditions. A warning is given, however, against the misinterpretation of artificial phenomena in the endeavour to elucidate natural occurrences.

The formation of graphite in firebricks from gaseous compounds of carbon may have significance for theories of the origin of natural graphite-deposits.

Phenomena occurring during the wet-mixing of earthenware are of interest to the sedimentary petrologist.

The manipulation of plastic ceramic clays or bodies produces petrofabric arrangements that can be matched in rocks. Structures found in the unfired body may persist as palimpsests in the fired ware.

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Cement and Ceramics Section
Division of Industrial Chemistry
Council for Scientific and Industrial Research
Australia

REVIEWS

Fear, War and the Atom Bomb; by P. M. S. Blackett. Pp. vii, 244. New York, 1949 (Whittlesey House, McGraw-Hill Book Co.). Two schools of thought may be discerned among physicists who have written in a popular or political vein about the atomic bomb. The first may be called the idealist school. Its numerous partisans were united by the conviction that the atomic event was so enormous, so unique and lethal in its social significance, as to invite an ignoration of all traditional political concerns and to demand the immediate institution of a world government to prevent war. Their efforts have come to naught for two reasons: one was the dissenting chorus of American voices, mostly from workers in the social sciences, which asserted that a neglect of history and of political institutions is unwarrantable and bound to be disastrous; the other was Russia.

The second school, adequately labelled realistic, though it was perhaps in sympathy with the aims of the idealists, tried to make the best of the actual situation and endeavored to integrate the problem of the atomic bomb with the other political problems of our time. It tended to minimize the importance of the bomb as a weapon and contemplated unflinchingly the possibility of an atomic war. Blackett is a leader of the realistic school and, furthermore, an apologist for Russia.

Commanding an unusual store of pertinent information, he analyses the facts surrounding the use of the bombs in Japan, the causes for the decision to use them, and the subsequent effects on international policy. He believes that diplomatic, not military expediency dictated the large-scale killing of civilians, implying that, in the minds of our leaders, the Japanese surrender to the Americans had to be secured before the Russian invasion developed too successfully. Because of the uniqueness of these motives, because of the improbability of their recurrence in another war, Blackett seems to feel that a wholesale use of atomic bombs on civilians in the future is not as likely as is often feared.

Another argument prominent throughout the book bears upon the Russian refusal to adopt the American (Baruch) plan for the control of atomic weapons. The key to an understanding of this attitude, Blackett thinks, is in the need Russia has for atomic energy in peaceful pursuits. Her energy output is low and for that reason she has a low standard of living. America, with her high rate of production, can easily afford to propose measures that will impede the development of atomic resources on a world-wide scale, which according to the author the Baruch plan will do. Russia stands to

gain far more from non-military applications of recent discoveries than the U. S., and more from non-military uses than from military ones.

Only a very small part of the book is devoted to the author's own proposals, which are interesting but none too effective; for when the reader has reached the last section, where advice is given, his worry about the soundness of the author's daring arguments has become inveterate and his responsiveness is low.

The idealists have said: let us disregard history; let us build anew. The early realists have surveyed the historical facts in their entirety and have based predictions upon them, often oblivious to the limited predictive qualities of present historical analyses. Blackett analyses with care, though with some obvious bias, the *scientific* facts of the situation and assumes that they provide a basis for historical prediction.

Somehow, I find Blackett's errors less interesting and less commendable than the errors of the idealists. HENRY MARGENAU

Quantum Mechanics; by L. I. SCHIFF. Pp. xii, 404. New York 1949 (McGraw-Hill Book Company, $5.50). A textbook suitable for a one-year graduate course in quantum mechanics. The treatment is modern, succinct; the topics are on the whole well chosen and reflect present-day interests in theoretical physics. As compared with other books in this field, its coverage is very complete and reasonably elegant. It is unique in its inclusion of an introduction to quantum electrodynamics, but it achieves this virtue by an omission of other important topics, such as quantum chemistry and the quantum theory of metals. HENRY MARGENAU

Principles of Petroleum Geology; by CECIL G. LALICKER. Pp. xii, 377; 67 tables, 157 figs., 8 pls. New York, 1949 (Appleton-Century-Crofts, Inc., $5.00). This book is apparently designed as a text for a beginning course in petroleum geology. The early chapters sketch a brief history of the subject and give an extended discussion of the physical and chemical properties of petroleum. Launching into geological matters the author presents an array of opinions regarding the origin of petroleum and its migration and accumulation. Reservoir rocks and oil structures are discussed, and numerous examples of oil fields, selected by mode of origin, are described. The current geophysical and other discovery methods are presented and explained. The closing chapters give a summary of geological considerations in recovery methods and the ways in which oil and gas properties are evaluated. No formal bibliography is included

in the book, but frequent references are made to the literature by means of standard footnotes.

One might question whether petroleum geology has any established principles; Mr. Lalicker's review of its literature leaves one in doubt on this point. In the reviewer's opinion, the book would be strengthened by a more rigorous treatment of the physics and chemistry in the discussion of the properties of petroleum. The voluminous stratigraphic tables of oil fields would be rendered more valuable by indicating the producing horizons in some way on the charts themselves. Similarly, the many structure contour maps, which are adequately located by township or county, would be more useful if small state index maps were added. Notably absent is any mention of the recovery possibilities from oil shale, such as the Green River formation.

The book presents much valuable material, but its value would be enhanced greatly by revision with particular attention directed to the organization.

JOHN E. SANDERS

PUBLICATIONS RECENTLY RECEIVED

Our Sun; by Donald H. Menzel. Philadelphia, 1949 (The Blakiston Company, $4.50).

New Mexico Bureau of Mines and Mineral Resources. Ground-Water Report 1. Geology and Ground-Water Resources of the Eastern Part of Colfax County, New Mexico; by Roy L. Griggs. 1948. $3.00.

Instituto Geologico Del Peru. Boletin 11. Datos Sismologicos Del Peru. 1947 by E. Silgado F. Lima 1948.

Instituto Geologico Del Peru. Boletin 10. Heologia De Los Rios Apurimac Y Urubamba; by Arnold Heim. Lima 1948.

Pennsylvania State College Bulletin. A Philosophy For Conservation; by Edward Steidle. School of Mineral Industries, State College, Pennsyvlania. 1949.

A Further Contribution to the Ichthyology of Venezuela; by Leonard P. Schultz. Washington; 1949. Smithsonian Institute, U. S. National Museum.

Colloid Science I and II; by A. E. Alexander. 1949 (The Oxford University Press).

Terrestrial Magnetism and Electricity; Edited by J. A. Fleming. New York, 1949 (McGraw-Hill Book Company, Inc.. $4.95).

Hydrology; Edited by Oscar E. Meinzer. New York, 1949 (McGraw-Hill Book Company, Inc., $4.95).

The Pulsation Theory of Variable Stars; by Svein Rosseland (Oxford University Press, $5.00).

Landscape; by C. A. Cotton. New York, 1949 (John Wiley & Sons, Inc., $10.00).

Introduction to Radiochemistry; by Gerhart Friedlander and Joseph W. Kennedy. New York, 1949 (John Wiley & Sons, Inc., $5.00).

Hydrology; by C. O. Wisler and E. F. Brater. New York, 1949 (John Wiley & Sons, Inc., $6.00).

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